INTRODUCTION

With the development of the mining, the overlying stratification moves, deforms, or ruptures once the coal seam is extracted. Thus, a “vertical three zone” can be formed. When the mine gob expands to a sufficient space, the roof strata will cave. As a result, the overlying strata continue to bend and break until the piles of fallen rock fragments are sufficiently high to support the overhanging strata. At this time, the overhanging strata are no longer to cave, but to bend in the underlying strata or gob piles. Bending of these strata develops upward until reaching the surface and forms a subsidence basin, causing surface subsidence and cracking, which is called ground subsidence.
Abundant onsite experience and laboratory studies show that the overlying strata and ground subsidence may result in massive damages to various types of surface systems such as ground buildings, land, and surface water systems.\textsuperscript{9,11} Moreover, subsurface strata movements form a large number of cracks in the overburden strata, which lead to the leakage of underground gas or water and also greatly impact on the stability of underground tunnels, water reservoir, and wells.\textsuperscript{12-14} In order to prevent the damage of surface ground or underlying strata and the situation of excessive gas in the underground caused by mining, it is of great significance to accurately predict the deformation of the rock and discuss the distribution of stress-porosity-permeability in the rock mass comprehensively.

Most researches employed multianchor borehole wire extensometers to perform real-time onsite monitoring on underlying strata subsidence over a large-scale gob.\textsuperscript{15-18} Although this direct field monitoring test technology could provide intuitive and first-hand information on the movement of overlying strata, it is not always the best method because of high costs and long operating time. On the other hand, numerical simulation methods make it possible to predict and analyze strata movements by using numerical calculations. For examples, the probability integration method could not only predict surface movement and deformation during coal mining operations,\textsuperscript{19-23} but also the settlement location of groundwater leakage cracks.\textsuperscript{24,25} The BP neural network,\textsuperscript{26} with an effective nonlinear fitting, is able to reflect the variation trend of mining subsidence in metal mines under a complicate environment. The finite element method\textsuperscript{27,28} and the finite difference method\textsuperscript{5,29} are capable to decompose strata into numerous tiny units for gridding and predict the movements between the mining level and the surface. In recent years, researchers have investigated different effects induced by parameters when carrying out numerical simulation calculations with an effort to predict the movement and deformation of coal seams. Someone uses the strata thickness, the excavation depth,\textsuperscript{30,31} and the underground permeability as influence factors to simulate the subsidence effects of coal seams.\textsuperscript{32,33} Since the permeability, stress, and porosity are dynamically changing and interacting with each other when subsurface strata move,\textsuperscript{34} it is necessary to comprehensively explore the relationship among those three. At present, the comprehensive discussion on the strain-porosity-permeability mostly occurs in the fields of oil and gas exploitation,\textsuperscript{35} groundwater exploitation,\textsuperscript{36} and drainage irrigation. Hence, considering the deformation characteristics in zones of overlying strata under coal mining, this study develops a corresponding numerical model to calculate the stratigraphic motion. Based on such models, another integrated numerical model is also developed to describe the strain-porosity-permeability of strata.

2 \hspace{0.5cm} MINING-INDUCED OVERLYING STRATA MOVEMENT MODEL AND STRAIN-POROSITY-PERMEABILITY MODEL

2.1 \hspace{0.5cm} Strata Movement Model in fracture zone and bending zone

The Knothe’s influence function is the most successful one that has been adapted by many major coal-producing countries. It states that the distribution of the subsidence caused by the extraction of one unity area can be expressed by a modified normal probability distribution function. The influence functions for subsidence and horizontal displacement in two-dimensional case (good for predicting final subsidence horizontal displacement along major cross-sections) are shown in Equation (1) and (2).\textsuperscript{37}

\[
f_s(x') = \frac{m \cdot a}{R} e^{-\frac{(x')^2}{\pi}} \tag{1}
\]

\[
f_u(x') = -\frac{2 \pi m \cdot a}{RH} x' e^{-\frac{(x')^2}{\pi}} \tag{2}
\]

where \( m \) is the mining height, \( a \) is the subsidence factor, \( R \) is the radius of major influence, \( x' \) is the horizontal distance between the extracted element and the surface point where final subsidence is to be calculated and \( H \) is the mining depth.

The derived mathematical expressions for the final subsidence and horizontal displacement at the surface point \( x \) are

\[
S(x) = \frac{m \cdot a}{R} \int_{d-x}^{w-d-x} e^{-\frac{(x')^2}{\pi}} dx' \tag{3}
\]

\[
U(x) = \frac{2 \pi m \cdot a}{RH} \int_{d-x}^{w-d-x} x' e^{-\frac{(x')^2}{\pi}} dx' \tag{4}
\]

where \( d \) is the offset of inflection point and \( W \) is the longwall panel width.

To broadly apply the models into subsurface strata for predicting the subsurface strata movement, significant modifications should be made. The proposed mathematical model for predicting subsurface strata movement would address the mentioned problems.\textsuperscript{38} The subsurface strata movement can be determined as the following procedure:

Collecting the geologic columnar profile over the underground longwall panel and naming the stratum from immediate roof to the surface as 1st, 2nd, 3rd, …, nth rock layer as Figure 1.
Defining the subsurface influence function. It should be noted that the influence functions defined here for the vertical and horizontal movements, which are applied in studying subsurface subsidence, would generate different results, such as inverted parabolas profiles that represent the subsurface strata movement and horizontal movement, at different rock layers. The following Equation 39 is used for subsurface subsidence along a major cross-section:

\[
f_s(x', z_i) = \frac{S_{\text{max}}(z_{i-1}) \cdot a_i}{R_i} e^{-\frac{x'}{R_i}} \quad i = 1, 2, \ldots, n \tag{5}
\]

In this equation, the coordinate \(x'\) is the horizontal distance between the point of “influence” to cause subsidence and the prediction point on the top surface of the layer. The term \(S_{\text{max}}(z_{i-1})\) is the predicted maximum final subsidence of the past layer \(z_{i-1}\), which can be obtained from the calculation results for the last layer. \(a_i\) and \(R_i\) are the subsurface strata movement factor and radius of major influence for the \(i\)th layer. For the first layer immediately above the mined coal seam, the mining height should be used in the place of \(S_{\text{max}}(z_{i-1})\) in the influence function. \(^{40}\)

The influence function for horizontal displacement along a major cross-section is derived from the influence function for subsidence (Equation 6) as shown in the following equation.

\[
f_h(x', z_i) = -2\pi \frac{S_{\text{max}}(z_{i-1}) \cdot a_i}{R_i \cdot \varepsilon_i} x' \cdot e^{-\frac{x'}{\varepsilon_i}} \quad i = 1, 2, \ldots, n \tag{6}
\]

Integrating the influence function within a proper horizontal interval for the final subsurface subsidence and horizontal displacement.\(^{41}\)

Similar to calculate the surface deformation using the influence method, the final subsurface subsidence and horizontal displacement at a prediction point \((x, z_i)\) are obtained by integrating influence functions between left and right inflection points at the corresponding rock layer as shown in Equations (7) and (8). In equations, \(W\) is the width of the mined longwall panel and \(d_i\) is the offset of inflection point.

\[
S(x, z_i) = \frac{S_{\text{max}}(z_{i-1}) \cdot a_i}{R_i} \int_{d-x}^{W-d-x} e^{-\frac{x'}{R_i}} \, dx' \quad i = 1, 2, \ldots, n \tag{7}
\]

\[
U(x, z_i) = -2\pi \frac{S_{\text{max}}(z_{i-1}) \cdot a_i}{R_i \cdot \varepsilon_i} \int_{d-x}^{W-d-x} x' \cdot e^{-\frac{x'}{\varepsilon_i}} \, dx' \quad i = 1, 2, \ldots, n \tag{8}
\]

### 2.2 Strata Movement Model in Caving Zone

#### 2.2.1 Calculation of extreme spans for initial breakage and periodic breakage of the strata

Two parameters, the extreme span \((L_i)\) of the initial caving of the strata and the extreme span \((L_{ip})\) of the periodic caving of the strata, are required to determine the initial or the periodic caving, which occurs once the length of the suspending strata is longer than the corresponding extreme span.\(^{42}\)

**Extreme span of initial caving of the strata**

The strata break down when its suspension length reaches the extreme span and then accumulate in the gob. Then, the extreme span of the fracture failure can be inferred by analyzing the supporting mechanical model of strata. In practical situations, the stress state of the strata is very complicated. In order to simplify the analysis process, the strata can be simplified to clamped beam for calculation and be simplified to the cantilever beam after initial breakage for continuing the calculation related to the periodic breakage.

According to the rock mechanics theory, the Mohr-Coulomb yield criterion is usually used in the engineering calculation as the criterion for distinguishing shearing and breakage. The Griffith criterion is used as the criterion for the rock strength of the tension stress damage. \(^{43}\) These theories can be similarly used as the criterion for distinguishing the breakage of the overlying strata breakage under mining. Before the initial breakage of the overlying strata under mining, the strata can be considered as the clamped beam by means of elasticity and the stress state of the clamped beam can be obtained as shown in Figure 2. The horizontal stress of clamped beam in coordinates is calculated according to Equation (9)\(^{44}\):

\[
\sigma_x = \frac{q(L - 6h^2 - 3\mu h^2)}{2h^3} y - \frac{6q}{h^3} x^2 y + \frac{4q}{h^3} y^3 \tag{9}
\]
In the Eq: $l$—suspension length of the strata, m; $h$—thickness of the strata, m; $\mu$—rock Poisson's ratio; $q$—overlying load of the strata, Pa.

When $x = \pm 1/2$ and $y = h/2$, the horizontal stress $\sigma_x$ can be calculated according to Equation (10):

$$
\sigma_x = \frac{q l^2}{4h} + \frac{1}{4}(3\mu - 2)q
$$

When $\sigma_x$ exceeds the tensile strength $[\sigma_x]$ of the strata, the strata damage. The extreme span of the initial breakage of the strata is calculated according to Equation (11):

$$
L_j = h \sqrt{\frac{4[\sigma_x] + q (3\mu - 2)}{q}}
$$

In the Equation (11), $L_j$ indicates the extreme span of the strata if the breakage is in the form of the clamped beam. Once the suspension length of the strata reaches or exceeds such value, the overlying strata suffer the initial breakage.

**Extreme span for initial breakage of the strata**

When the strata suffer the initial breakage, as the underground working face continues to advance, the strata on one side of working face can be considered as a cantilever beam. The strata similar to the cantilever beam in the ground pressure control may suffer periodic breakage, thus to form the periodic pressure. When the cantilever beam bears deadweight and uniform load, horizontal stress $\sigma_x$, vertical stress $\sigma_y$, and total stress $\tau_{xy}$ are calculated according to Equation (12), (13), and (14), respectively:

$$
\sigma_x = \frac{q}{h^2} \left( \frac{3}{5}h^2 + 6\chi^2 - 4\gamma^2 \right) y + 4\gamma \frac{y^3}{h^2} - 6\gamma \frac{x^2 y}{h^2}
$$

$$
\sigma_y = \frac{q}{2} \left( 1 - \frac{3}{h} y + 4\frac{y^3}{h^3} \right) - 2\gamma \frac{y^3}{h^2} + \frac{1}{2} \gamma y
$$

$$
\tau_{xy} = -\frac{3q}{2h} \left( 1 - \frac{4\gamma^2}{h^2} \right) x - 6\gamma \frac{xy^2}{h^2} + \frac{3}{2} \gamma x
$$

When $x = L$ and $y = h/2$, $\sigma_x = \frac{3Lj^2}{h} \left( \frac{q}{h} - \gamma \right) - \frac{q}{5} + \frac{1}{2} \gamma h$; when $\sigma_x$ exceeds the tensile strength $[\sigma_x]$ of the strata, the strata damage and the extreme span of cantilever beam strata is shown in Equation (15):

$$
L_{ij} = h \sqrt{\frac{10[\sigma_x] + 2q - 5\gamma h}{30(q - \gamma h)}}
$$

In the Equation (15), $L_{ij}$ indicates the extreme span of the strata when the breakage is in the form of the cantilever beam. Once the mining length of working face reaches or exceeds $L_j + L_{ij}$, the overlying strata start to suffer the periodic breakage.

### 2.2.2 Calculation of Subsidence Movement of Breakage Strata

After the initial breakage of the strata, as the mining continues to advance, the strata on one side of the working face suffer the continuous periodic breakage in the form of the cantilever beam and the strata on the side of open-off cut are considered as the cantilever beam. Therefore, the strata above it are suffering the periodic breakage, and the state of the cantilever beam strata on the side of open-off cut keeps relatively stable.

The bended and deformed curve of the strata on one side of the working face can be calculated by employing the deflection curve equation of the cantilever beam under the uniform load in elasticity and material mechanics, as shown in Equation (16):

$$
S_{ab}(x,i) = -\frac{q\chi^2}{24EI} \left( \chi^2 - 4\chi x + 6x^2 \right)
$$

In the Equation (16), the value range of $l$ is $0, L_{ij}$. As the working face advances and the suspension length $l$ of the cantilever beam strata increases, once $l$ is equal to $L_{ij}$, it shows the strata complete a periodic breakage and start a new periodic movement. Therefore, the horizontal length of subsidence curve of certain cantilever beam strata always varies as the working face advances, as immediate roof, main roof, and strata region in the third layer of overlying strata in dashed line frame one side of the working face as shown in Figure 3. The strata on one side of open-off cut are considered as the cantilever beam, as strata region in left dashed line frame. However, suspension lengths of immediate roof,
main roof, and the third layer of strata are fixed. Therefore, it can be considered that the cantilever beam strata on one side of the open-off cut are consecutive after the strata suffer breakage and the calculation results by strata movement model established based on influence function method are followed. Because the state of the cantilever beam strata on one side of open-off cut is relatively stable, the horizontal distance from the right end of the cantilever beam on the left on the \( n^{th} \) layer to the open-off cut can be calculated by the following Equation (17):

\[
 L_{\text{ub}}(n) = \sum_{i=1}^{n} L_{sj} \quad (17)
\]

For broken rocks filling most space of the gob, the rock may suffer the volume expansion compared with the in situ stress condition, namely the embodiment of the broken expansion. This characteristic is one of the important causes for preventing the continuous breakage of the strata in the fractured zone. Therefore, after breakage and accumulation of the strata, the residual broken expansion coefficient \( K_r \) is employed to calculate subsidence and horizontal displacement of the strata. Without considering the expansion of the strata in the tendency, subsidence and horizontal displacement of caving and breakage part of the strata on the \( i^{th} \) layer can be calculated by the following Equations (18) and (19):

\[
 S_{\text{ml}}(x,i) = -m + \sum_{i=1}^{n} \left( \sqrt{1 + K_r h} - 1 \right) \times h_i \quad (18)
\]

\[
 U_{\text{ml}}(x,i) = \sqrt{1 + K_r h} \times U(x,z_i) \quad (19)
\]

In the Equations: \( m \) — mining height, m; \( K_r \) — residual broken expansion coefficient of rock, dimensionless; \( h \) — thickness of the strata, m.

### 2.2.3 Calculation process of Strata movement model

In the advancing process of the working face, the movement of the overlying strata is a dynamic process. The roof strata suffer the initial breakage firstly, and the roof strata on the mining side of the working face form the cantilever beam as the advancing distance \( W \) of the working face increases.
After the immediate roof (the first layer of the strata) suffers the breakage, the upper layer of the strata (the second layer of the strata) still bears a certain load. Therefore, the second layer of the strata can be considered as the clamped beam with the continuous initial breakage of the strata until the end of the mining. As the working face advances, the cantilever beam of the strata on one side of the working face continuously suffers the breakage. The upper strata may suffer the breakage after the suspension length of the clamped beam or the cantilever beam exceeds the extreme span.

The continuity of the numerical model established based on influence function method is not suitable for calculating the movement of the broken strata. Therefore, conditions for the breakage of the strata should be discussed. Figure 4 shows the judgment of a point \((x, z_i)\) on the \(i\)th layer of the strata and the chart of calculation process.

2.3 | The Study of permeability distribution in strata of overlying vertical three zones

The rock permeability is the main parameter characterizing the rock permeability. When the overlying strata are affected by mining, factors such as in situ stress and temperature change to different degrees, while the permeability of the strata may vary with these factors. Generally speaking, when the coal seam is mined, the overlying strata are disturbed and broken and bended to different degrees forming “vertical three zone” from underground to surface, as shown in Figure 5:

In order to more scientifically reveal the movement of the overlying strata with the mining coal seam as well as the produced fracture distribution and development and to finally provide theoretical and technical basis for underground gas control, the established strata movement model is combined in this paper to study on the change law of the permeability with the rock stress after the rock strata subside and move.

2.4 | Model of Strain-Porosity-Permeability change in Overlying Strata

In the mining process of coal seam, the emission of gas causes extreme threat to the mine safety production. The coal rib, the broken coal pieces, and the gob are three sources of gas emission, in which gob gas contributes a relatively high proportion of gas emission. The caving zone mainly focuses on the pore permeability, fractured zone, and bending zone focus on fracture permeability.

The fractured in the overlying strata under mining can be studied according to characteristics of overlying strata zoning: (a) caving zone: It is the porosity-fractured zone; (b) fractured zone and bending zone: They are main development regions of fractures. The value solution method and influence
2.4.1  Determination of permeability of porous coal of caving zone

The caving zone is mainly formed by accumulation of residual coal and broken rocks, and the diffusion method of gas is mainly the movement in the form of laminar and diffusion. The permeability of caving zone can be expressed as Equation (20):\(^{46}\)

\[
K_k = \frac{K_0}{0.241} \left[ \frac{\phi^3}{(1-\phi)^2} \right] (20)
\]

where \(K_k\) — permeability of caving zone, \(\text{m}^2\); \(\phi\) — porosity, \%; \(K_0\) — original permeability of the strata, \(\text{m}^2\).

The porosity \(\phi\) of the strata can be calculated according to the following Equation (21):

\[
\phi = \frac{\phi_0 + \varepsilon_f}{1 + \varepsilon_f} (21)
\]

where \(\phi_0\) — strata original porosity of the strata, \%; \(\varepsilon_f\) — total strain of strata, \(\text{mm/m}\).

The total strain \(\varepsilon_t\) of the strata can be calculated by the horizontal stress \(\varepsilon_x\) and the vertical stress \(\varepsilon_z\) produced by the strata, and Equation (22) and Equation (23) are obtained by taking the derivative of the Eq.:

\[
\varepsilon_x = \frac{dU(x,z)}{dx} (22)
\]

\[
\varepsilon_z = \frac{dS(x,z)}{dz} (23)
\]

The total strain \(\varepsilon_t\) is shown in Equation (24):

\[
\varepsilon_t = \varepsilon_x + \varepsilon_z + \varepsilon_x \varepsilon_z (24)
\]

The strata may suffer breakage when the suspension length reaches the extreme span, and the broken rocks may accumulate in the gob, mainly focusing on the porosity development. Equation (24) is substituted into Equation (20) to obtain Equation (25) for calculating the permeability of the caving zone:

\[
K_k = \frac{K_0}{0.241} \left[ \frac{\left( \frac{\phi_0 + \varepsilon_f}{1 + \varepsilon_f} \right)^3}{\left( 1 - \frac{\phi_0 + \varepsilon_f}{1 + \varepsilon_f} \right)^2} \right] (25)
\]

2.4.2  Determination of fracture permeability in fractured zone and bending zone

The fractures with different widths are distributed in the fractured zone of the overlying strata. For fracture and length in the rock, the permeability can be expressed as Equation (26) by using the parallel plate model,\(^{47}\) in which the fracture width \(b\) is calculated by the tension fracture, as shown in Equation (27),\(^{48}\) and the fracture depth \(Z\) involved in the calculation process can be calculated according to Equation (28):

\[
K_{ft} = \frac{\rho_f g b^3}{12} (26)
\]

\[
b = C_x Z (27)
\]

\[
Z = E \varepsilon_x / \left[ 1000 \rho_r (1 + v) \right] (28)
\]

where \(K_{ft}\) — permeability of fracture per unit area and length, \(\text{m}^2\); \(\rho_f\) — fluid density, \(\text{kg/m}^3\); \(g\) — gravitational acceleration, \(\text{m/s}^2\); \(b\) — fracture width, \(\text{m}\); \(C_x\) — proportional coefficient, usually 0.003–0.015; \(Z\) — fracture depth, \(\text{m}\); \(E\) — elastic modulus, MPa; \(\varepsilon_x\) — horizontal strain, \(\text{mm/m}\), which can be calculated according to Eq. (22); \(\rho_r\) — bulk density of the strata, \(\text{kN/m}^3\); \(v\) — Poisson’s ratio.

Equation (22), Equation (27), and Equation (28) are substituted into Equation (26) to obtain the Equation (29) for calculating the permeability of the unbroken strata in fractured zone and bending zone:

\[
K_{ft} = \frac{\rho_f g C_s \left[ \frac{E \varepsilon_x (x,z)}{1000 \rho_r (1 + v)} \right]^3}{12} (29)
\]

2.4.3  Calculation process of “vertical-three-zone” permeability model

In continuous mining, the overlying strata of the working face suffer initial breakage and periodic breakage to form caving zone, above which are fractured zone and bending zone in turn. The calculation process of strain-porosity-permeability model established aiming at “vertical three zone” is shown in Figure 6, and a point \((x, z_i)\) on the \(i\)th layer of the strata is taken for an example. The involved parameters, such as the horizontal strain \(\varepsilon_x\) of strata and the total strain \(\varepsilon_t\) of strata, should be obtained by taking the derivative of Eqs for calculating horizontal and vertical movement of the strata. Therefore, the permeability of overlying strata under mining should be associated with the displacement, strain, and porosity of the overlying strata under mining.
3 | CASE STUDY OF OVERLYING STRATA MOVEMENT MODEL IN AN UNDERGROUND WORKING FACE

3.1 | Background of Working Face

For mining of #15 coal seam in a mine, the width of the working face is 230 m and the length is 1584 m. The average thickness of coal seam is 6.6 m. The maximum mining depth is 526 m, and the average mining depth is 468 m. Figure 7 shows part of physical parameters of comprehensive geological histogram #15 coal seam and the corresponding strata, and all studied overlying strata lithology and relevant physical parameters are shown in Table 1.

3.2 | Comparative analysis of calculation results of strata movement model and 3DEC numerical simulation results

3.2.1 | Overlying strata movement using 3DEC modeling

The 3DEC simulation software is a simulation software based on discrete element method, which can be used to study the movement of the strata bearing static load or dynamic load under noncontinuum. Before establishing the overlying strata numerical model, main steps include the following:

Selecting correct and appropriate constitutive model, which can ideally reflect the mechanical behavior of strata
under mining. 33 3DEC simulation software provides three constitutive models aiming at movement of blocks, and Mohr-Coulomb constitutive model is usually selected as the constitutive model for simulation of strata movement. Because the rock is considered as block in the simulation process, Mohr-Coulomb constitutive model is selected as constitutive model complying with overlying strata of working face for resolution.

Preliminary research and data collection. The main purpose is to select reasonable physical-mechanical parameters. Mohr-Coulomb constitutive model involves massive basic physical parameters, which should be set and perfected in advance, such as rock density, elastic modulus, Poisson’s ratio, internal friction angle, cohesion, and tensile strength. Parameters of the strata are determined and shown in Table 2. Once determined the specific value of physical parameters of strata, the physical parameters of contacts could be obtained from the empirical value based on whole strata’s in-stope physical parameters, and parameters of the interface between blocks are shown in Table 3 after the division of blocks.

Setting of boundary condition. According to the stress environment of the strata, appropriate stress and speed boundary conditions are selected. The height of the strata involved when simulating the movement of overlying strata of the working face is 74.32 m, and 16 MPa of pressure is loaded on the top layer of the strata surface.

### Table 1 Physical parameters of all overlying strata

| Layer number | Lithology                                      | Thickness m | Elasticity Modulus GPa | Body force MN/m³ | Tensile strength MPa | Poisson ratio |
|--------------|-----------------------------------------------|-------------|------------------------|------------------|-----------------------|---------------|
| 12           | Sandy mudstone                                | 5.00        | 18.91                  | 0.017            | 2.00                  | 0.15          |
| 11           | Coarse-grained sandstone                      | 6.20        | 39.56                  | 0.020            | 1.00                  | 0.22          |
| 10           | Mudstone, limestone                           | 9.07        | 16.68                  | 0.021            | 2.50                  | 0.27          |
| 9            | Coal seam                                     | 0.50        | 1.30                   | 0.013            | 0.60                  | 0.32          |
| 8            | Medium- and fine-grained sandstone and mudstone | 10.29       | 26.00                  | 0.019            | 1.20                  | 0.27          |
| 7            | Coal seam                                     | 0.79        | 1.30                   | 0.013            | 0.60                  | 0.32          |
| 6            | Mudstone, limestone, fine-grained sandstone   | 11.66       | 21.00                  | 0.018            | 2.50                  | 0.27          |
| 5            | Coal seam                                     | 0.53        | 1.30                   | 0.013            | 0.60                  | 0.32          |
| 4            | Fine-grained sandstone                        | 9.75        | 27.38                  | 0.024            | 1.00                  | 0.24          |
| 3            | Mudstone                                      | 6.92        | 27.69                  | 0.020            | 0.61                  | 0.26          |
| 2            | Limestone and fine-grained sandstone          | 6.70        | 20.32                  | 0.025            | 1.80                  | 0.24          |
| 1            | Sandy mudstone                                | 8.73        | 16.05                  | 0.016            | 2.00                  | 0.15          |

### Table 2 Relative physical parameters of overlying strata block

| Layer number | Lithology                                      | Bulk modulus Pa | Shear modulus Pa | Friction angle ° | Cohesion Pa | Tensile strength Pa |
|--------------|-----------------------------------------------|-----------------|-----------------|-----------------|-------------|---------------------|
| 12           | Sandy mudstone                                | 1.90E + 10      | 9.50E + 10      | 25              | 7.85E + 05  | 1.00E + 06          |
| 11           | Coarse-grained sandstone                      | 6.00E + 10      | 2.00E + 10      | 30              | 1.37E + 06  | 5.80E + 06          |
| 10           | Mudstone, limestone                           | 2.80E + 10      | 1.20E + 10      | 18              | 1.50E + 06  | 1.22E + 06          |
| 8            | Medium- and fine-grained sandstone and mudstone | 3.50E + 10    | 1.78E + 10      | 27              | 8.90E + 05  | 1.00E + 06          |
| 6            | Mudstone, limestone, fine-grained sandstone   | 3.40E + 10      | 1.70E + 10      | 20              | 3.50E + 06  | 1.45E + 06          |
| 4            | Fine-grained sandstone                        | 1.90E + 10      | 9.50E + 10      | 25              | 7.85E + 05  | 1.00E + 06          |
| 3            | Mudstone                                      | 2.80E + 10      | 1.20E + 10      | 18              | 1.50E + 06  | 1.22E + 06          |
| 2            | Limestone and Fine-grained sandstone          | 1.90E + 10      | 9.50E + 10      | 25              | 7.85E + 05  | 1.00E + 06          |
| 1            | Sandy mudstone                                | 2.80E + 10      | 1.20E + 10      | 18              | 1.50E + 06  | 1.22E + 06          |
### Table 3: Relative physical parameters of contacts between overlying strata blocks

| Layer number | Lithology                                | Shear stiffness Pa | Normal stiffness Pa | Cohesion $c_{\text{ho}}$/Pa | Friction angle ° | Tensile strength Pa |
|--------------|------------------------------------------|-------------------|--------------------|-----------------------------|----------------|-------------------|
| 12           | Sandy mudstone                           | 5.50E + 09        | 5.30E + 09         | 1.40E + 05                  | 32             | 1.50E + 06        |
| 11           | Coarse-grained sandstone                 | 2.00E + 09        | 1.50E + 09         | 8.00E + 05                  | 25             | 9.00E + 05        |
| 10           | Mudstone, limestone                      | 1.80E + 09        | 1.20E + 09         | 6.00E + 05                  | 19             | 1.40E + 06        |
| 8            | Medium- and fine-grained sandstone and mudstone | 5.00E + 09  | 2.00E + 09         | 1.00E + 05                  | 25             | 1.10E + 06        |
| 6            | Mudstone, limestone, fine-grained sandstone | 4.70E + 09        | 3.50E + 09         | 1.20E + 05                  | 30             | 1.60E + 06        |
| 4            | Fine-grained sandstone                   | 5.50E + 09        | 5.30E + 09         | 1.40E + 05                  | 32             | 1.50E + 06        |
| 3            | Mudstone                                 | 1.80E + 09        | 1.20E + 09         | 6.00E + 05                  | 19             | 1.40E + 06        |
| 2            | Limestone and fine-grained sandstone     | 5.50E + 09        | 5.30E + 09         | 1.40E + 05                  | 32             | 1.50E + 06        |
| 1            | Sandy mudstone                           | 1.80E + 09        | 1.20E + 09         | 6.00E + 05                  | 19             | 1.40E + 06        |

### Table 4: The initial break span and the periodic break span of each layer in the overburden

| Layer number | Lithology                                | Thickness m | Extreme span for initial breakage m | Periodic breakage span m | Residual broken expansion coefficient $K_{\rho}$ |
|--------------|------------------------------------------|-------------|-------------------------------------|--------------------------|-----------------------------------------------|
| 12           | Sandy mudstone                           | 5.00        | 48.10                               | 14.06                    | 1.1                                           |
| 11           | Coarse-grained sandstone                 | 6.20        | 29.28                               | 8.85                     | 1.08                                          |
| 10           | Mudstone, limestone                      | 9.07        | 65.61                               | 19.29                    | 1.11                                          |
| 9            | Medium- and fine-grained sandstone and mudstone | 0.50      | 9.59                                | 2.77                     | 1.07                                          |
| 8            | Mudstone, limestone, fine-grained sandstone | 10.29     | 38.02                               | 11.74                    | 1.15                                          |
| 7            | Fine-grained sandstone                   | 0.79        | 12.05                               | 3.49                     | 1.07                                          |
| 6            | Mudstone                                 | 11.66       | 63.46                               | 18.92                    | 1.1                                           |
| 5            | Limestone and fine-grained sandstone     | 0.53        | 9.87                                | 2.85                     | 1.07                                          |
| 4            | Sandy mudstone                           | 9.75        | 38.00                               | 11.69                    | 1.1                                           |
| 3            | Lithology                                | 6.92        | 28.13                               | 8.60                     | 1.12                                          |
| 2            | Sandy mudstone                           | 6.70        | 43.51                               | 12.86                    | 1.11                                          |
| 1            | Coarse-grained sandstone                 | 8.73        | 53.86                               | 15.94                    | 1.15                                          |

### 3.2.2 Comparative analysis of calculation results of strata movement model and simulation results

In order to study the development of porosity and fracture in the overlying strata over the working face, the movement of 12 layers of strata in 76.14 m range over the working face is calculated. It is very important to judge whether the strata suffer the initial breakage as well as the periodic breakage. The extreme span for the initial strata breakage, the periodic breakage span, and the residual broken expansion coefficient $K_{\rho}$ of the corresponding strata blocks after the breakage are shown in Table 4.

One of the very important factors for the suspended subsidence and the movement of the overlying strata in the gob is the broken expansion of blocks in the caving zone. When the rock suffers the breakage after liberated under the in situ stress, the volume of broken rocks may suffer a certain expansion. When the volume increment after the expansion of broken and accumulated rock completely fills the volume of the mined out space, the strata above the caving zone at this time will not continue the breakage. Figures 8 and 9 show breakage times, predicted movement curve, and simulated movement of strata of overlying strata when the working face advances to 50 and 150 m. The schematic of the breakage of the overlying strata shows the initial breakage and the periodic breakage of the strata, and the 3DEC numerical simulation shows the trend of the strata with the movement of the working face in the mining process. It can be
calculated according to data listed in Table 4 that when the advancing distance of the working face reaches 149.46 m, after #1–#4 stratum suffers 4–8 times of periodic breakage, the suspension length of #8 stratum reaches the extreme span of initial breakage, which suffer breakage. After the expansion of breakage rocks in #1–#8 stratum, the height expands from original 55.87 to 62.56 m and the increment is 6.7 m, while the thickness of the mining coal seam is 6.6 m. Therefore, it can be considered that the volume of breakage blocks in #1–#8 stratum after expansion has filled the gob volume caused by mining. The strata above #8 strata will no longer has fierce breakage phenomenon. In the whole advancing process of the working face (advancing length is between 150 m and 1584 m), the height of overlying strata of the working face in gob in caving zone is #1–#8 stratum, 55.37 m of height from the coal seam.
Figure 8 shows breakage law of overlying strata, movement curve, and simulated strata when the working face advances to 50 m. Upon calculation, the length of initial breakage of coal seam immediate roof ( #1 stratum) is 53.86 m; therefore, the strata are only bended and deformed but not broken, and the movement of the whole overlying strata is only limited to the bended and deformed movement. Therefore, fractured zone and bending zone are only formed on the whole overlying strata. The movement prediction curve of the strata shows that the subsidence and movement curve of coal seam immediate roof have obvious flat-bottom phenomenon. From simulation results, the immediate roof near one side of open-off

**FIGURE 9** The overlying strata subsidence prediction curves and simulation when the working face advanced to 150 m
cut has almost breakage sign, which reflects 1# strata will suffer initial breakage. The calculated subsidence quantity of 1#~12# strata of the whole overlying strata reaches 1.2~6.6 m, and the radius of the subsidence basin of the strata increases as the vertical distance of coal and rock increases.

When the working face advances to 150 m, 1#~8# strata suffer the breakage, and the height of broken rocks can balance the coal seam thickness after the broken expansion. Therefore, the maximum height of the development of the caving zone is 55.37 m, while simulation results show the development height of the caving zone reaches 57.3 m, as shown in Figure 9(3). Three obvious separation fractures occur in the overlying strata on one side near the working face. Figure 9(1) shows that 8# strata suffer two times of periodic breakage; at the same time, 3# strata suffer up to 10 times of periodic breakage, while 6# strata suffer one time of periodic breakage, and other strata, respectively, suffer 5~7 times of periodic breakage. The cantilever beam strata on one side of the working face after the breakage of the strata are shown in broken circle in Figure 9(2), and lengths of the cantilever beam are, respectively, 0.5 m (1#), 0.03 m (2#), 6.54 m (3#), 9.08 m (4#), 2.38 m (6#), and 1.96 m (8#). Figure 9(3) shows the result of simulated strata movement. After 8# strata suffer breakage, the height of the caving zone continues to develop compared with the working face advancing to 100 m, the height (55.42 m) of subsidence prediction curve of 8# strata in the gob is almost near the original height (55.37 m), namely, rocks accumulate after the breakage of 1#~8# strata, because the height of the rock after the volume expansion reaches the height of 8# strata, the strata above 8# strata will

### Table 5
The comparative analysis of strata subsidence using 3DEC simulation and mathematical model calculation when the working face advancing distance varying from 0 meter to 200 meters

| Face advance distance/m | Monitoring line | Subsidence/m | Strata number |
|-------------------------|----------------|--------------|---------------|
|                         | NO.1-4         | 3DEC Simulation and Model Calculation | 1# 2# 3# 4# 6# 8# 10# 11# 12# |
| 0                       |                 | 0 0 0 0 0 0 0 0 0 | 0 0 0 0 |
| 50                      | NO.1           | 3DEC Simulation | 2.4 1.2 0.89 0.76 0.53 0.42 0.39 0.39 0.38 |
|                         |                 | Model Calculation | 6.6 3.4 2.1 1.64 1.01 0.8 0.74 0.45 0.39 |
|                         |                 | Error | 4.2 2.2 1.21 0.88 0.48 0.38 0.35 0.06 0.01 |
|                         |                 | Error Rate | 63.6% 64.7% 57.6% 53.7% 47.5% 47.5% 47.3% 13.3% 2.6% |
| 100                     | NO.1           | 3DEC Simulation | 6.6 6.6 6.53 6.45 4.5 4.2 4.05 2.9 2.2 |
|                         |                 | Model Calculation | 6.6 6.6 6.6 6.6 5.3 4.6 4.25 3.8 2.7 |
|                         |                 | Error | 0 0 0.07 0.15 0.8 0.4 0.2 0.9 0.5 |
|                         |                 | Error Rate | 0.0% 0.0% 1.1% 2.3% 15.1% 8.7% 4.7% 23.7% 18.5% |
|                         | NO.2           | 3DEC Simulation | 5 4.6 4.3 4 3 2.9 2.7 2.3 2.29 |
|                         |                 | Model Calculation | 6.6 6.6 6.6 5.46 4.31 3.6 3.2 2.79 2.78 |
|                         |                 | Error | 1.6 2 2.3 1.46 1.31 0.7 0.5 0.44 0.49 |
|                         |                 | Error Rate | 24.2% 30.3% 34.8% 26.7% 30.4% 19.4% 15.6% 15.8% 17.6% |
| 150                     | NO.1           | 3DEC Simulation | 6.6 6.6 6.57 6.55 6.1 4.5 4.05 2.9 2.2 |
|                         |                 | Model Calculation | 6.6 6.6 6.6 6.6 6.3 4.6 4.15 3.76 2.78 |
|                         |                 | Error | 0 0 0.03 0.05 0.2 0.1 0.1 0.86 0.58 |
|                         |                 | Error Rate | 0.0% 0.0% 0.5% 0.8% 3.2% 2.2% 2.4% 22.9% 20.9% |
|                         | NO.2           | 3DEC Simulation | 6.6 6.6 6.6 6.6 5.81 3.6 3.4 1.9 1.54 |
|                         |                 | Model Calculation | 6.6 6.6 6.6 6.6 6.25 5.83 5.6 5.3 5.1 |
|                         |                 | Error | 0 0 0 0 0.44 2.23 2.2 3.4 3.56 |
|                         |                 | Error Rate | 0.0% 0.0% 0.0% 0.0% 7.0% 38.3% 39.3% 64.2% 69.8% |
|                         | NO.3           | 3DEC Simulation | 1.6 1.24 0.91 0.83 0.78 0.64 0.58 0.54 0.46 |
|                         |                 | Model Calculation | 2.31 1.89 1.78 1.45 1.3 1.12 0.89 0.75 0.57 |
|                         |                 | Error | 0.71 0.65 0.87 0.62 0.52 0.48 0.31 0.21 0.11 |
|                         |                 | Error Rate | 30.7% 34.4% 48.9% 42.8% 40.0% 42.9% 34.8% 28.0% 19.3% |
| 200                     | NO.1           | 3DEC Simulation | 6.6 6.6 6.57 6.55 6.1 4.5 4.05 2.9 2.2 |
|                         |                 | Model Calculation | 6.6 6.6 6.6 6.6 6.4 4.9 4.35 3.46 2.68 |
|                         |                 | Error | 0 0 0.03 0.05 0.3 0.4 0.3 0.56 0.48 |
|                         |                 | Error Rate | 0.0% 0.0% 0.5% 0.8% 4.7% 8.2% 6.9% 16.2% 17.9% |
not have obvious breakage phenomenon because of the support of broken rocks in the process of bending and sinking.

Four monitoring lines are taken along the trend in the operational process of 3DEC simulation and numerical model, respectively, 25, 75, 125, and 175 m from the open-off cut. Nine subsidence displacement monitoring points are taken according to strata stratification of each monitoring line vertically, located in the middle of the strata. As the working face advances, the simulation and comparison of simulation calculation results are shown in Table 5. The comparative analysis of the difference in both is shown in Figure 10, and the basic trend of 3DEC simulation results and model calculation results is consistent in the subsidence process of overlying strata. When the working face advances to 50m, the error between simulation results and model calculation results is large, which corresponds to 50m (No.1) in Figure 10, reaching the maximum 4.2 m; as the working face continues to advance to 150 and 200 m, the error at 10#, 11#, and 12# strata on No.2 monitoring line is large, as 150 m (No. 2) and 200 m (No. 2) shown in Figure 10; the error range of simulation and model calculation of other monitoring comparison point is 0.11~2.3 m.

4  |  APPLICATION OF PERMEABILITY DISTRIBUTION MODEL IN MINING-INDUCED OVERLYING STRATA

4.1  |  Permeability evolutionary calculation of overlying strata

Combining the existing subsidence model with strain-porosity-permeability relation employed, the permeability distribution model of overlying strata in gob is obtained. To obtain distribution prediction of the permeability $K$ of the overlying strata under advancing length condition of different working faces as shown in Figures 11 and 12, which involves part of strata, parameters (bulk density $\rho_r$, Poisson’s ratio $\nu$, elastic modulus $E$) can refer to data of 1#~12# strata in Table 2. The original porosity $\phi_0$ of the strata and original porosity $K_0$ is shown in Table 6.

According to relevant research findings of petrophysical phase of gas reservoir and the permeability of coal reservoir described by well log, the strata are divided into three different levels and types according to the permeability of the strata, namely I-level highly permeable area, the permeability is more than 1 md; II-level moderately permeable area, the permeability is between 0.1 and 1 md; and III-level lowly permeable area, the permeability is less than 0.1 md. When the advancing distance of the working face is 50 m, the mining effect has the small disturbance to the overlying strata. Therefore, all the overlying strata are considered being in fractured zone or bending zone and the variation range of the permeability is small, approx. 0.6~1.7 md. Only the permeability of part strata near the coal seam significantly changes, as the strata area with distances from A, B, C, and D less than 32.1 m from coal seam shown in Figure 11. The strata below 5# strata, in which the area (B, C) of the blue isoline is the area where the permeability decreases compared with the original rock permeability, which is usually less than the original permeability of the corresponding strata and the range is 0.6~1 md belonging to II-level moderately permeable area. The strata area (A, D) of red isoline far away from the middle of gob is the area where the rock increases. The range is 1~1.7 md, belonging to I-level highly permeable area.

![Image 10: Comparison between 3DEC simulation results and model calculation results](image-url)
The permeability of other strata above 5# strata increases or decreases; however, the variation range of the permeability and the affected rock range are small. A’, B’, and C’ in Figure 11 are, respectively, areas where 6#–12# strata are disturbed, and the permeability of the strata in this area slightly increases or decreases.
When the working face advances to 150 m, the change distribution of permeability $K$ of overlying strata in gob is shown in Figure 12. At this time, the advancing length of such working face just reaches the length (149.46 m) of completed development of overlying strata in caving zone, and the final development height in caving zone is 55.37 m, namely the accumulated thickness of 1#~8# strata. From Figure 12, the maximum area of permeability $K$ is 1#~4# strata (B), near coal seam, and the next is 5#~7# strata (B’), which increases by 12.45 m in the height of area B’ in Figure 11, and the permeability of 8# and 9# strata increases to a certain extent. The maximum permeability of 1#~3# strata is 5.4 md, and B belongs to I-level highly permeable area; the maximum permeability of 4#~7# strata is approx. 3.2 md, and B’ belongs to II-level moderately permeable area, the permeability is between 0.4 and 1 md.

### 4.2 Design of high-level drainage roadway of working face and assessment of effects

The permeability of coal and surrounding rock of the working face is small, and emission quantity of gas is nearly from the coal seam before breakage of the strata in gob and the relative gas emission quantity is below 10 m$^3$/t. However, after strata breakage, gas of surrounding rock emits largely to the working face of coal mining with the mining fracture. The absolute gas emission quantity of the mine reaches 190 m$^3$/min, in which over 90% of gas comes from the adjacent coal seam and surrounding strata.

The average thickness of #15 coal seam of working face is 6.6 m, and the height of fractured zone locates between 39...
and 230 m over #15 coal seam and the high-level drainage roadway of working face is finally designed at the position at 52 m from #15 coal seam over the working face.

Figure 13 shows a plan view for arrangement of high-level drainage roadway of working face. The gas tube pipeline arranged in high-level drainage roadway is connected to ground gas extraction pump station. The horizontal distance from high-level drainage roadway to return airway of working face is 20 m, and the vertical distance from the working face is 52 m. Fractures develop in the “O” form range over the long-wall panel. Such areas are good for doing gas extraction. The forming negative pressure by the gas pump at the upper corner of the working face could effectively extract and gather mine gas in strata and around working face.

According to the observation daily report of high-level drainage roadway of the working face, as shown in Table 7, it shows that gas flowrate drained by the return airway and tail roadway is 0.08~0.1 m³/min; the gas flowrate of high-level drainage roadway takes a large proportion in total emission of gas and extraction flowrate reaches 39.2~45.85 m³/min, with the proportion up to above 96.58%. Thus, it can be seen that high-level drainage roadway of working face is the most important gas extraction way of the working face, which can effectively control the gas concentration of the working face.

5 | CONCLUSIONS

Because the overlying strata over the mine gob may form different movement states of caving zone, fractured zone, and bending zone after affected by the mining, different calculation models for strata movement are established. Reliability validation is carried out by using numerical simulation method. The strain-porosity-permeability relation of the strata is studied, and different basic equations of the calculation permeability are employed aiming at the “vertical three zone” of overlying strata under mining. The prediction analysis model of strain-porosity-permeability of the strata is developed. It is applied to an actual working face, which shows the variation situation of the permeability after deformation and destruction of upper overlying strata after mining. Through the engineering practice of designing the high-level drainage roadway of a working face, the gas extraction efficiency is improved, which also show developed models with the good application value.

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