Research on the Mining Effect of Floor Strata in Deep Coal Seam Mining: A Case Study of #7 Coal Seam at Chazhuang Coal Mine

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Abstract. Studying the mining effect of floor strata in deep coal seam mining is beneficial for evaluating and relieving the risk of water inrush from the floor. In addition, such research forms the basis for ensuring the support and stability of roadways and chambers in the lower part of the coal seam. By considering the mining of #7 coal seam in the 7600 deep mining area of the Chazhuang coal mine in Feicheng coalfield as the engineering background, this study analyzes the distribution law of mining abutment pressure and the range of failure depth affected by mining using elastic theory. In addition, the stress, strain, and failure states of the floor rock mass affected by mining are comprehensively simulated and studied using the FLAC3D finite difference software combined with field measurement results of rock movement in the lower roadway of the #7 coal seam. The mining effect of the floor is further compared and studied, providing a scientific reference basis for realizing the safe mining of coal in confined water in the deep lower group of the Feicheng coalfield.

1. Introduction

The deep coal seams under the threat of floor-confined water cause large ground stress and high water pressure during mining. Floor water invasion is a major disaster that can occur during deep coal seam mining in case of this type of coal mine [¹-³]. The shallow part of the Feicheng coalfield in Shandong Province has been mined. The deep coal seams, particularly #7, #8, and #9, are threatened by the confined water of the fourth limestone, the fifth limestone, and Ordovician limestone aquifers at the bottom floor. The aquifuge from the limestone aquifer to the coal seam is thin, ranging from a few to a dozen meters. When the water pressure of the limestone under pressure is considerably high, the thin water barrier exhibits insufficient water barrier capacity. When the water-breaking layer is partially damaged by mining to form a water inrush channel, a floor water inrush accident will occur when the mining face exposes these areas [⁴-⁵]. Therefore, based on the example of the #7 coal seam in the 7600 deep mining area of Chazhuang coal mine, it is considerably important to study the mining effect of...
deep coal seam mining to realize the safe mining of deep coal at a pressure greater than the confined pressure in the Feicheng coal field.

2. Engineering background
The #3 coal seam of the Permian Shanxi Formation and the #7, #8, #9, and #10 coal seams of the Carboniferous Taiyuan Group are the main mining seams in Chazhuang coal mine. The development mode of the mine is vertical multi-level, with a main roadway and cross-cuts. Four vertical shafts are present: one auxiliary shaft, one main shaft, and two air shafts that include a central air shaft and north air shaft. In addition, four mining levels of −150, −250, −350, and −550 m are utilized. The 7600 deep mining area is the downhill mining area for the −350-m level, and the #7 coal seam above −415 m has been mined safely. Owing to the influence of faults, mining below −415 m is this area is threatened by water from the fourth limestone, the fifth limestone, and Ordovician limestone. The average distance between the #7 coal seam and the fourth limestone is 20.6 m. The lithology is mainly argillaceous cemented siltstone with poor cementation and easy expansion when in contact with water.

The inclined length of the test working face is 52–80 m, with an average of 57.5 m, and the strike length is 460 m. The average thickness of the #7 coal seam is about 1.5 m. The direct roof is composed of siltstone with a thickness of 5.0 m, and the main roof and direct bottom are composed of fine sandstone with thicknesses of 3.0 m and 4.0 m, respectively. Longwall working face backward mining technology is adopted, and the roof is managed by the all caving method.

To detect the influence of mining on the floor, the 8600-drainage roadway was arranged in the fourth limestone about 20 m below the floor of the test working face of the #7 coal seam to observe the stress and strain, and the results are used to analyze the mining effect of the upper coal seam.

3. Theoretical analysis of mining effect on floor

3.1. Abutment pressure distribution of floor rock mass
After a coal seam is mined, the stress in the equilibrium state is destroyed, and the original stress is redistributed. A zone of stress change then develops near the mining area and results in stress concentration. The stress concentration is strongest near the mining layer.

The stress state in the floor rock mass also undergoes a series of changes. According to the FLAC3D numerical simulation results and the actual recorded observations, the peak supporting pressure in the coal bed floor rock is within a certain distance in front of the coal wall of the working face, and its distance from the coal wall depends on the elastoplastic deformation of the coal body. The results of actual measurement and numerical analysis indicate that the influence range of the front support pressure is 20–25 m; the distance from the peak support pressure to the coal wall is generally 0–15 m; the side support pressure range is 15–20 m, and the coal bed floor rock inside the goaf The body is in a state of pressure relief.

3.2. Scope of floor rock mass mining failure
In the process of coal seam mining, as shown in Figure 1, the direct roof, the old roof, and other rock beams of the overburden are sequentially destroyed. The stress of the floor of the working face first increases then decreases before rising to the original rock stress value. The floor rock layer experiences compression, expansion, shearing, and other effects [6-7]. Statistics show that the floor is prone to water inrush accidents during the mining of the working face. Therefore, research on the stress and strain of the floor rock mass is key for understanding its failure state and the possibility of water inrush [8].
The stress increment before and after coal mining is shown in Figure 2. The maximum value of the stress increment is \((K - 1)P_0\). In the calculation, the stress increment at the center of the coal seam is regarded as the load of the plane body. According to the Saint-Venant principle, the two forces acting on a small part of the boundary of an object are transformed into differently distributed but equivalent surface forces. Although the stress distribution in the vicinity will change significantly, the impact on the distance can be ignored \([9]\).

![Figure 1. Structural diagram of roof overburden.](image)

According to the theory of elastic mechanics, we get the following formulas.

\[
\sigma_1 = \frac{(K - 1)P_0z}{\pi} \left[ \frac{1}{a_1} (1 - \tan \theta_1) (\theta_2 - \theta_1) - \frac{1}{a_2} (1 - \tan \theta_3) (\theta_3 - \theta_2) \right] \\
+ \frac{P_0z}{\pi} \left[ \frac{1}{a_4} (1 - \tan \theta_5) (\theta_6 - \theta_4) - \frac{1}{a_3} (1 - \tan \theta_3) (\theta_4 - \theta_3) \right] \\
\sigma_3 = \frac{(K - 1)P_0z}{\pi} \left[ -\frac{1}{a_1} (1 + \tan \theta_1) (\theta_2 - \theta_1) + \frac{1}{a_2} (1 + \tan \theta_3) (\theta_3 - \theta_2) \right] \\
+ \frac{P_0z}{\pi} \left[ -\frac{1}{a_4} (1 + \tan \theta_5) (\theta_6 - \theta_4) + \frac{1}{a_3} (1 + \tan \theta_3) (\theta_3 - \theta_2) \right]
\]

Substituting the Mohr-Coulomb criterion results in

![Figure 2. Schematic diagram of stress increment calculation of the bottom plate.](image)
\[ \sigma_1 - m\sigma_3 = R_C. \]  

The obtain the floor damage area, we calculate
\[ Z = \frac{\pi R_C a_1 a_2 a_3 a_4}{A P_0} \]  

and
\[ A = [(m+1) + (m-1)\tan \theta_1]a_2 a_3 a_4 (K - 1) (\theta_2 - \theta_1) \]
\[ - [(m+1) + (m-1)\tan \theta_2]a_1 a_3 a_4 (K - 1) (\theta_3 - \theta_2) \]
\[ - [(m+1) + (m-1)\tan \theta_2]a_1 a_2 a_4 (\theta_4 - \theta_3) \]
\[ + [(m+1) + (m-1)\tan \theta_4]a_1 a_2 a_3 (\theta_5 - \theta_4) \]

where \( \sigma_1, \sigma_3 \) is the principal stress at point o in the bottom plate; \( P_0 \) is the original ground stress, where \( P_0 = \gamma H \); \( \gamma \) is the average density of the rock layer; \( H \) is the mining depth; and \( K \) is the advanced bearing stress coefficient of the working face.

The above formula is based on the assumption that the floor rock mass is an ideal homogeneous material. When calculating the failure depth of the floor, deviations will inevitably occur. With the development of computer application technology and engineering application software, numerical simulation methods make up for the deficiencies in this area owing to their flexibility, convenience, and accuracy. Thus, such methods are used in increasing numbers of applications.

4. Comparative study on numerical simulation and measurement of mining effect on floor

The failure characteristics and depth of the floor aquifuge under the mining effect play important roles in evaluating the risk of floor water inrush. On the basis of the actual spatial relationship between the working face and the drainage roadway, the corresponding drainage roadway model was established in the numerical simulation, and the monitoring points corresponding to the actual observation pressure gauge and dynamic instrument were set up.

4.1. Basic equations of the elastoplastic finite element method

The characteristics of the calculation area indicate generally an elastic range, which belongs to the elastic model. Because part of the area undergoes plastic yield failure, it can be treated as an elastoplastic model. Generally, elastoplastic problems include the following basic equations. The balance equation is
\[ \sigma_{i,j} + f_i = 0; \]  

the stress–strain equation is
\[ \sigma_y = f(\epsilon_y); \]  

and the yield function is
\[ f(\sigma_y, \epsilon_y) = 0. \]

In addition, the displacement or stress boundary conditions need to be considered. After solving the above basic equations, the finite element method can be used to analyze the stress and strain distribution of the structure as well as its stability.

The elastoplastic finite element transforms the basic governing equations into linear algebraic equations through variational principles and discretization and then transforms the continuous field
function of the area to be solved into the field function value at a finite number of discrete points. Obviously, this discretization processing is an approximation; therefore, satisfactory solution accuracy can be guaranteed only if the unit is divided sufficiently small parameters.

After discrete analysis, the strain of the element can be expressed as

$$\{\varepsilon\} = [B] \{\delta\}^e,$$  \hspace{2cm} (9)

where $[B]$ is the element strain matrix, and $\{\delta\}^e = [u_1, u_2, \ldots, u_n]$ is the function at the element node.

After the element strain is obtained, the constitutive equation of the material is used to calculate the element stress as

$$\{\sigma\} = [D] \{\varepsilon\} = [D] [B] \{\delta\}^e.$$  \hspace{2cm} (10)

After discretization, the overall balance equation is

$$[K] \{\delta\} = \{R\},$$  \hspace{2cm} (11)

where $[K]$ is the global stiffness matrix of the structure, $\{R\}$ is the equivalent nodal force of the node, and $\{\delta\}$ is the displacement of the node.

4.2. Numerical model and mesh generation

The numerical model consists of 163200 elements and 172569 nodes. Its geometric dimensions are 120 m, 180 m, and 131.5 m along the X, Y, and Z directions, respectively. Because this study focuses on the floor failure of the #7 coal seam after mining, and the boundary effect needs to be eliminated, the roof of this coal seam is taken upward about 40 m, and the floor of the seam is taken down to the Ordovician limestone, about 92 m. The upper surface of the model is constrained by uniform loading, which is the weight of rock strata from the upper boundary of the model to the surface; the lateral boundary is constrained horizontally; and the bottom boundary is constrained horizontally and vertically, which is the fixed boundary condition.

The design plan in the calculation analysis is the first mock exam from the cut hole, and 9 m is the simulated mining step. Owing to time limitations, the mining activity simulation was stopped after 135 m. The calculation range and mesh generation are shown in Figure 3.

![Figure 3. Mesh generation and schematic diagram of discharge roadway.](image-url)
4.3. Simulation analysis of mining effect on floor

Because the study investigates mainly the deformation and failure of a floor affected by mining, the floor stress, strain, and failure range obtained by simulation are determined under the condition of coal mining.

4.3.1. Analysis of stress characteristics for floor rock mass. With the working face mining forward, the stress in the coal seam roof and floor changed obviously from the initial stress field with uniform distribution.

As shown in Figure 4, when mining for 18 m, the stress in the floor on both sides of the goaf increased; however, the value and range of the stress increase was obviously not as high as that of the roof. Moreover, a small drop in stress occurred in the middle of the floor of the goaf. When the working face advanced to 90 m, mining was fully achieved. In addition, the area of stress increase on both sides of the goaf and the area of stress decrease under the middle part of the floor were maximum. When the working face continued to advance to the stoppage line, i.e., to 135 m, as shown in Figure 5, the influence scope of the maximum and minimum principal stresses reached the fourth limestone layer.

On the basis of these results combined with the mechanical strength values of the coal seam roof and floor, the following conclusions were drawn. In the area of stress increase on both sides of the goaf floor, plastic deformation is produced owing to stress concentration to form compression and a shear failure area. In the middle part of the goaf floor, a tensile failure zone is formed owing to the decrease in tensile stress.

![Figure 4. Chromatogram of maximum principal stress at 18 m.](image1)

![Figure 5. Chromatogram of maximum principal stress at 135 m.](image2)

4.3.2. Analysis of strain characteristics for floor rock mass. After coal seam mining, the original rock stress state of the rock surrounding the coal seam is destroyed, and the surrounding rock stress is...
redistributed. The resulting change in the magnitude or type of stress will cause the floor rock layer to deform or even break after advancing to a particular distance on the working surface. When the working face was advanced to 18 m, upward strain appeared in the floor; that is, a kick drum was produced. At that time, the floor affected by mining was 3–5 m below the coal seam, which had not affected the fourth limestone layer. When the working face advanced to 36 m and 54 m, the floor rock strata affected by mining reached the fourth limestone strata. After advancing to 90 m, the working face reached full mining. From the perspective of the depth of the floor rock layer affected by mining, however, the fifth limestone layer was reached. When the working face advanced to 135 m, its depth affected the Ordovician limestone aquifer, as shown in Figures 6 and 7.

The above analysis indicates that the floor area affected by the #7 coal seam mining was symmetrical on both sides of the goaf. After the #7 coal mining, the Ordovician limestone aquifer became involved in terms of the stress influence range.

![Figure 6. Strain chromatogram of bottom plate when pushing 90 m.](image)

![Figure 7. Strain chromatogram of bottom plate when pushing 135 m.](image)

### 4.3.3. Failure state analysis of floor rock mass.

Coal mining inevitably causes redistribution of the surrounding rock stress of the roof and floor. If the stress after redistribution exceeds the strength limit of the rock, it will inevitably lead to rock damage. As shown in Figure 8, when the working face advanced to 18 m and 36 m, owing to the influence of stress redistribution, the floor rock layer sustained a certain degree of damage. When the working face advanced to 54 m, 72 m, and 90 m, the failure depth increased accordingly, and the scope of the damage area also increased. When the working face advanced from 90 m to 108 m, 126 m, and 135 m, at which point it reached the stop line, the depth of the floor unit failure was essentially unchanged (Figure 9). This also indicates that when the working face advanced to 90 m, full mining was reached.
In the simulation process, the weak rock layers with small mechanical parameters in the model were easily affected to the first state after being affected by mining. Thus, the different lithological combinations of rock layers have an important influence on whether damage occurs and the degree of damage after being affected by mining.

![Figure 8. Chromatogram of damage state of bottom plate when pushed to 36 m.](image)

![Figure 9. Chromatogram of damage state of bottom plate when pushed to 135 m.](image)

4.4. Simulation analysis of mining effect on floor

The observation results of the dynamic changes of the corresponding observation points in the 8600 drainage roadway are shown in Figure 10. Before the working face advanced to 90 m, the value changes observed at each measuring point were small. When the working face advanced to 90 m, the value of measuring point #6 suddenly increased and was more strongly affected by mining; when the measuring point #4 was pushed over 100 m on the working face, its value gradually increased. This shows that the impact of mining on the 8600 drainage roadway will not be obvious when the working face is not mined to 90 m. With the progression of the working face, the impact of mining on the 8600 drainage roadway gradually became obvious, whereas the impact on individual places was more severe. Roof falling or spalling provides evidence of this phenomenon.
5. Conclusion
On the basis of theoretical analysis, numerical simulation, and field measurement of the mining effect on the floor in the 7600 deep mining area of Chazhuang coal mine, the following conclusions can be drawn.
(1) The mining of the deep coal seam is increasingly under seriously threat of floor water invasion. To ensure safe mining under high water pressure, it is necessary to clarify the possible influence and scope of mining in the floor.
(2) The area in the floor affected by mining is symmetrical on both sides of the goaf. From the perspective of the stress influence range, Ordovician limestone is involved; therefore, attention should be paid to this unit in actual production.
(3) Floor rock layers of different lithological combinations have different sensitivities to damage after mining. The more complete the rock mass structure, the greater the rock mass strength, the smaller the mining damage, the smaller the impact of groundwater on it, and the better the water blocking performance.
(4) The results of the numerical simulation are essentially consistent with the actual monitoring results, particularly from the perspective of the depth and scope of the damage caused by mining of the working face floor. This also shows that it is feasible to use FLAC3D numerical simulation software to study the coal floor mining effect.
(5) The mining effect on the floor is comprehensively affected by various factors such as the nature of the rock mass, mining, and confined water. In future research, various factors should be fully considered to reflect the characteristics of mining failure more realistically and to guide safe deep-seam mining on a more scientific basis.

Acknowledgments
The research was funded by the National Natural Science Foundation of China (51774199). The authors are thankful for all of the support for this basic research.

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