Research Article

Study on Mechanical Evolution Characteristics of Overburden Rock in “Knife Handle”-Type Fully Mechanized Top-Coal Caving Face

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Compared with that of equal-length working faces, the mechanical evolution mechanism of overburden rocks in "knife handle"-type mining sites is more complex. The form of roof fracture of knife handle-type mines is more variable, and the stress distribution near the interface is more concentrated, thereby severely threatening the safety of mining. To elucidate the mechanical evolution characteristics of rocks in knife handle-type fully mechanized top-coal caving mining sites, the geological conditions of the 22401 fully mechanized knife handle top-coal caving face in Hanjiawa coal mine are investigated. FLAC3D software is used to numerically simulate the abutment pressure, horizontal stress, and vertical displacement of the fully mechanized knife handle top-coal caving face. This provides an effective theoretical and technical framework for subsequent problems, such as mine pressure control, roof management, and support withdrawal under similar mining conditions. The simulation results indicate that when the working face is mined within the range 20–30 m before and after the knife handle caving, the stress distribution is considerably asymmetric, the abutment pressure and horizontal stress are overconcentrated, the maximum vertical stress is 18.41 MPa, and the maximum horizontal stress is 16.45 MPa. Influenced by mining stress and self-weight, the roof subsides and the floor bulges. The maximum sinkage of the roof is 268.9 mm and the maximum bottom drum displacement is 10.01 mm.

1. Introduction

Since the conception of the wall-type coal mining system, a regular arrangement has been followed for the working face, which has a constant tendency length, to ensure the safe and efficient mining of the working face. Since the beginning of the twenty-first century, the increasing demand for the coal has led to an increased intensity and depth of coal mining, and "knife handle"-type mining sites have emerged, such as the Shigefje coal mine in Lu’an, Xutuan coal mine in Huaibei, and Shendong mine in Inner Mongolia [1]. Scholars in China and abroad have conducted several studies from different perspectives by adopting different methods and theories on the movement law of the overburden rock for mining regular working faces with constant tendency lengths. The masonry beam theory developed by Academician Qian et al. [2] states that with the advancement of the working face, the masonry beam structure formed after the breakage of the overburden rock is a determinate structure. Furthermore, the magnitude of the horizontal thrust required to form the masonry beam structure is directly proportional to the breakage length and load of the
overburden, inversely proportional to the layer thickness and sinking amount, and independent of the stress distribution in the mining area. Zhang [3] analyzed the overburden damage law under the couple effects of stress field and seepage field at the mining site of a shallow coal seam covered with a thick loose layer and rich groundwater using RFPA2D-Flow numerical simulation software. The results indicated that when the mine roof approaches collapse and destabilization under mining stress and self-weight, the water pressure of the seepage field notably influences the overburden damage. When the overburden breaks, it interacts with the seepage field, leading to abrupt changes of seepage coefficient, groundwater flow, and groundwater head of the seepage field. Zhang et al. [4] used similar simulation experiments in conjunction with the bore-laneway resistivity method to accurately obtain the height of the overburden collapse zone and the hydraulic conductivity fracture zone during the mining process. Wang [5] used FLAC3D numerical simulation software to analyze the relationship between stress evolution and advancement distance of the regular working face and “positive-handle” and “negative-handle” fully mechanized mining faces. The results indicated that mining stress increases sharply when the working face is advanced to an integer multiple of the inclination length of the working face, and the accuracy of the conclusions is verified through engineering examples. Liu et al. [6] took the close-range coal seam as the research object, combined with the geological conditions of the Xiejiao coal mine, calculated the failure depth of the floor when the upper coal seam was mined, and provided the corresponding surrounding rock deformation control measures for the safe mining of the lower coal seam. Li et al. [7] analyzed the ground stress distribution under the regenerated roof geological conditions by means of numerical simulation and put forward the technical measures to strengthen the monitoring of surrounding rock activities and timely pressure relief during the mining process, which ensure the safe mining of the working face.

Compared with studies on regular mining sites with constant inclination length, fewer studies have investigated the overburden damage and stress evolution in irregular mining sites with abrupt changes in inclination length, especially in the fully mechanized top-coal caving face. This study investigated the evolution characteristics of the overburden mechanics of the knife handled fully mechanized top-coal caving field by combining the geological conditions of the top and bottom of coal seam 22# in Hanjiawa mine. FLAC3D software was used to numerically simulate the abutment pressure, horizontal stress, and vertical displacement of the “knife handled” fully mechanized top-coal caving field.

2. General Situation of the Mine

The Hanjiawa 22401 fully mechanized top-coal caving face is the first mining face in the Western Region; the total coal-sea thickness is 9.2~14.8 m, with an average thickness of 11.6 m. The coal seam inclination angle is 4°~11°, the average inclination angle is 6°, which is near horizontal coal seam. The ground elevation of the working face is 1550~1580 m, the underground elevation is 1263~1290 m, and the coal seam burial depth is about 200 m. The absolute gas gush from recovery is 0.82 m²/min and the gas grade is low. The strike length of the working face is 833 m. When mined toward the middle of the working face, the inclination length of the working face is abruptly reduced from 170 m to 120 m; at the working face inclination of 170 m, the strike length is 528 m, and at the working face inclination of 120 m, the strike length is 305 m. The single long-arm backward low top-coal caving mining method is adopted in the working face. The coal mining height is 3 m, the coal caving height is 8.6 m, and the mining and caving ratio is 1:2.87. The direction of mining advance is from west to east along the floor of the coal seam, and the fully mechanized caving method is used to manage the goaf. The layout of the working face is illustrated in Figure 1.

3. Numerical Simulation

3.1. Modeling. FLAC3D (Fast Lagrangian Analysis of Continua in 3 Dimensions) is a numerical calculation program developed by ITASCA, USA, and is based on the 3D explicit finite difference method. The program has an internal nested null unit model and 18 intrinsic models, including three elastic models and 15 plastic models, and can be used to satisfactorily simulate the 3D mechanical properties of materials. FLAC3D is extensively applied in the mining field, especially for the simulation of coal recovery and collapse processes in fully mechanized top-coal caving [8].

FLAC3D numerical simulation software was used to establish a model by combining the top and bottom rock layer column diagrams of the 22401 fully mechanized top-coal caving face with the corresponding physical and mechanical parameters of the coal rock body; and the model rock layer distribution visualization is illustrated in Figure 2. The model size is designed to be 800 m × 400 m × 100 m, with 297882 zones and 303211 grid points. The grids and nodes of the model are divided densely to reflect the stress distribution in the working face accurately. To eliminate the influence of the boundary conditions, the model is designed to be large enough, and 110 m of protective coal pillars are constructed at each end in the direction of the working face. In the direction of the inclination of the working face, 110 and 135 m of protective coal pillars are constructed on each side of the working face when the working face is large and small, respectively, with an inclination length of 170 and 120 m, respectively. The four sides of the model, front, back, left, and right, are selected as displacement constraint boundaries; that is, no displacement occurs in either the horizontal or vertical direction. The top and bottom of the model are selected as free boundaries, and their horizontal and vertical displacements are not constrained. A uniform load of 5 MPa is applied to the top of the model to simulate the weight generated by the overlying rock layer at burial depth of 200 m [9].
3.2. Parameter Design and Failure Criterion. This simulation uses Fish Language to control the model for simulating the mining activities of the roadway and working face. The Mohr-Coulomb intrinsic model in FLAC3D is selected for simulating the deformation and damage of the coal rock body, and its mechanical expression as follows:

\[
 f_s = \sigma_3 - \sigma_1 \frac{1 - \sin \varphi}{1 + \sin \varphi} + 2c \left( \frac{1 - \sin \varphi}{1 + \sin \varphi} \right) 
\]

(1)

where \( \sigma_3 \) is the minimum principal stress, \( \sigma_1 \) is the maximum principal stress, \( c \) is the cohesive force of the material (MPa), and \( \varphi \) is the internal friction angle of the material (°). The physical and mechanical parameters of the coal rock body at the 22401 working face are displayed in Table 1.

4. Analysis of Simulation Results

As the working face advances, the elastic-plastic energy accumulated in the overlying rock layer begins to release, and the stress induces redistribution and thus a new equilibrium state. Under the influence of mining action, the overburden stress approaches the mining goaf, thus forming a new abutment pressure zone and horizontal stress zone around the mining goaf and a mining stress field with overburden stress formed in front of the working face. The roof and floor are influenced by the double action of self-weight and mining stress field in each rock layer between the vertical and horizontal direction of movement, and a displacement field is formed according to the law of stress evolution [10].

4.1. Evolution Law of Abutment Pressure. In the mining process, the evolution law of abutment pressure in the fully mechanized top-coal caving face with variable face length can be obtained according to the distribution of vertical stress in the roof at different propelling distances. As illustrated in Figure 3, when the working face is propelled to 40, 120, 200, 280, 320, 340, 360, 400, 480, and 560 m, the corresponding vertical stress peaks are 10.07, 11.10, 12.46, 12.99, 16.38, 18.41, 16.06, 14.13, 12.97, and 12.36 MPa, respectively.
4.2. Characteristics of Horizontal Stress Distribution. The evolution law of the horizontal stress of the knife handle comprehensive mining site at the advancing distance can be obtained according to the horizontal stress distribution of the surrounding rock during the mining process. As illustrated in Figure 4, when the working face is propelled to 40, 120, 200, 280, 320, 340, 360, 400, 480, and 560 m, the corresponding horizontal stress peaks are 5.04, 5.96, 7.22, 11.48, 15.51, 16.45, 16.28, 15.40, 12.49, and 10.06 MPa, respectively. The abutment pressure increases with the increase in the propelling distance and is distributed symmetrically along the axis of the working face. The abutment pressure in the rock mass of the two grooves is notably higher than that in the coal seam roof. The maximum abutment pressure is distributed in the rock mass within the range of 0.75–1.25 m from the coal walls of the two grooves, and the minimum abutment pressure is distributed near the interface of the two roadways and the roof and floor.

While the working face is propelled to the vicinity of the knife handle, the abutment pressure increases abruptly, the static pressure transforms into dynamic pressure [11, 12], and the roof moves intensely, and the pressure is abnormal. Therefore, roadway maintenance becomes difficult. Furthermore, large separation cracks appear between some layers of the overlying strata, thereby causing interlayer dislocation. Compared with the roof stress on the operating roadway side, the roof stress on the air roadway side is more concentrated and exhibits an irregular distribution.

When the working face gradually transitions into the small face, the abutment pressure considerably decreases, the numerical fluctuation is small, and the rock strata activity is relatively mild. The stress is symmetrically distributed along the central axis of the working face, and the stress distribution of the roof is approximately arched. The stress in the rock mass on the air roadway side is slightly larger than that on the transport roadway side.

Within the propelling range of 0–280 m, the abutment pressure increases with the increase in the propelling distance and is distributed symmetrically along the roof and floor. When the working face is propelled to the vicinity of the knife handle, the abutment pressure increases abruptly, and the static pressure transforms into dynamic pressure [11, 12], and the roof moves intensely, and the pressure is abnormal. Therefore, roadway maintenance becomes difficult. Furthermore, large separation cracks appear between some layers of the overlying strata, thereby causing interlayer dislocation. Compared with the roof stress on the operating roadway side, the roof stress on the air roadway side is more concentrated and exhibits an irregular distribution.

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4.3. Variation Law of Overburden Displacement Field. Under the double action of mining stress and self-weight of the overburden rock, the layers of the roof and floor undergo relative misalignment and vertical movement, leading to the sinking of the roof and bulging of the floor [13]. Figure 5 illustrates the sinking intensity of the roof and the bulging intensity of the bottom slab when the working face advances to the vicinity of the knife handle. When the working face advances to the vicinity of the knife handle.

Table 1: Physical and mechanical parameters of coal and rock mass at the 22401 working face.

<table>
<thead>
<tr>
<th>Rock sequence</th>
<th>Rock</th>
<th>Thickness (m)</th>
<th>Density (kg/cm³)</th>
<th>Shear modulus (S/GPa)</th>
<th>Bulk modulus (B/GPa)</th>
<th>Internal stress (C/MPa)</th>
<th>Internal friction angle (°)</th>
<th>Tensile strength (T/MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sand shale</td>
<td>35</td>
<td>2910</td>
<td>3.5</td>
<td>4.3</td>
<td>30</td>
<td>30</td>
<td>3.2</td>
</tr>
<tr>
<td>2</td>
<td>Siltite</td>
<td>27</td>
<td>3350</td>
<td>5.1</td>
<td>6.5</td>
<td>5.4</td>
<td>42</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>Medium-grained sandstone</td>
<td>13</td>
<td>3628</td>
<td>4.6</td>
<td>6.5</td>
<td>6.0</td>
<td>40</td>
<td>4.0</td>
</tr>
<tr>
<td>4</td>
<td>Silty-mudstone</td>
<td>2.5</td>
<td>2610</td>
<td>3.3</td>
<td>4.8</td>
<td>4.6</td>
<td>38</td>
<td>3.5</td>
</tr>
<tr>
<td>5</td>
<td>Fine-grained sandstone</td>
<td>2.5</td>
<td>3019</td>
<td>5.4</td>
<td>6.7</td>
<td>4.9</td>
<td>34</td>
<td>4.1</td>
</tr>
<tr>
<td>6</td>
<td>Coal</td>
<td>14</td>
<td>1410</td>
<td>0.5</td>
<td>0.8</td>
<td>5.1</td>
<td>23</td>
<td>0.4</td>
</tr>
<tr>
<td>7</td>
<td>Fine-grained sandstone</td>
<td>2</td>
<td>2980</td>
<td>5.5</td>
<td>6.8</td>
<td>5.0</td>
<td>33</td>
<td>4.0</td>
</tr>
<tr>
<td>8</td>
<td>Coal</td>
<td>0.5</td>
<td>1320</td>
<td>0.3</td>
<td>0.7</td>
<td>1.9</td>
<td>20</td>
<td>0.3</td>
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<tr>
<td>9</td>
<td>Sand mudstone</td>
<td>3.5</td>
<td>2510</td>
<td>3.1</td>
<td>4.6</td>
<td>4.6</td>
<td>38</td>
<td>3.2</td>
</tr>
</tbody>
</table>
Figure 3: Cloud map of vertical stress distribution. (a) Vertical stress distribution cloud map at 40 m propulsion distance. (b) Vertical stress distribution cloud map at 120 m propulsion distance. (c) Vertical stress distribution cloud map at 200 m propulsion distance. (d) Vertical stress distribution cloud map at 280 m propulsion distance. (e) Vertical stress distribution cloud map at 320 m propulsion distance. (f) Vertical stress distribution cloud map at 340 m propulsion distance. (g) Vertical stress distribution cloud map at 360 m propulsion distance. (h) Vertical stress distribution cloud map at 400 m propulsion distance. (i) Vertical stress distribution cloud map at 480 m propulsion distance. (j) Vertical stress distribution cloud map at 560 m propulsion distance.
Figure 4: Cloud map of horizontal stress distribution. (a) Horizontal stress distribution cloud map. (b) Horizontal stress distribution cloud map at 40 m propulsion distance at 120 m propulsion distance. (c) Horizontal stress distribution cloud map. (d) Horizontal stress distribution cloud map at 200 m propulsion distance at 280 m propulsion distance. (e) Horizontal stress distribution cloud map at 320 m propulsion distance. (f) Horizontal stress distribution cloud map at 340 m propulsion distance. (g) Horizontal stress distribution cloud map at 360 m propulsion distance. (h) Horizontal stress distribution cloud map at 400 m propulsion distance. (i) Horizontal stress distribution cloud map at 480 m propulsion distance. (j) Horizontal stress distribution cloud map at 560 m propulsion distance.
advances to 325, 335, 345, and 355 m, the corresponding sinking of the roof is 254.2, 268.9, 238.3, and 205.9 mm, respectively, and the bulging of the floor was 9.73, 10.01, 9.6, and 10.3 mm, respectively.

Compared with the regular working face with constant tendency length, the working face in the vicinity of the knife handle causes the sinking intensity of the roof to increase significantly and causes the roof to move violently; then, the roof is destabilized and deformed, requires joint support, or weak pressure for reduced stress concentration and safe mining. Furthermore, the floor drum displacement does not fluctuate and is rather stable. The contour map of the top and bottom plate displacement is basin-shaped, with the displacement distributed symmetrically along the central axis of the coal mining face. The displacement of the top and bottom plate gradually decreases from the middle to either side.

5. Conclusion

This study investigated the distribution of abutment pressure, horizontal stress, and the displacement of the roof and floor in the mining process in the 22401 “knife-handle” fully mechanized top-coal caving face of the Hanjiawa mine. FLAC\textsuperscript{3D} numerical simulation software was used for simulation and analysis. The conclusions drawn based on the study results are as follows:

1. During the mining process, when the working face is far away from the knife handle, the abutment pressure increases with the increase in mining advance distance; within the range 20–30 m before and after the knife handle, the abutment pressure and horizontal stress both increase abnormally, and the stress distribution is notably asymmetric. The maximum abutment pressure and horizontal stress are 18.41 and 16.45 MPa, respectively, and the stress concentration is sufficiently high. When the working face leaves the knife handle and smoothly transitions to a small face, the abutment pressure and the fluctuation in the values decrease, and the mining abutment pressure at the small face is slightly larger than at the large. A certain correlation is noted between the evolution characteristics of abutment pressure and horizontal stress with the mining advance in the working face; both abutment pressure and horizontal stress influence the transport activities in the overlying rock layer.

2. The evolution trend of the horizontal stress and supporting stress is different. The advancing distance when the horizontal stress increases abnormally is considerably smaller than that when the abutment pressure increases abnormally. Thus, during the construction process, the problem of excessive concentration of horizontal stress should be addressed through prior intervention.

3. The roof sinks and the floor bulges because of the mining stress and self-weight. When the working face advances to the vicinity of the knife handle, the activity in the top plate is intense and the sinking intensity increases notably. The floor is more stable, with small fluctuations in the values. The contour map of the roof and bottom displacement is basin-
shaped, with the displacement distributed symmetrically along the central axis of the coal mining face. The displacement of the top and bottom plate gradually decreases from the middle to either side. The maximum sinkage of the roof is 268.9 mm and the maximum bottom drum displacement is 10.01 mm.

Data Availability
The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest
The authors declared no potential conflicts of interest with respect to the research, author-ship, and/or publication of this article.

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