Movement Law of Overlying Strata with Loading Effect in the Large Space Structure of Deep Mines

Cui Feng¹,²,³, Lei Zhaoyuan¹,²,³,⁴, Li Tuanjie⁴, Lv Zhaohai⁵, Li Lei⁴, and Dong shuai¹,²,³

¹Energy School, Xi'an University of Science and Technology, Xi'an, Shaanxi 710054, China;  
²Key Laboratory of Western Mines and Hazard Prevention of China Ministry of Education, Xi'an University of Science and Technology, Xi'an, Shaanxi 710054, China;  
³Key Laboratory of Coal Resource Exploration and Comprehensive Utilization, Ministry of Land and Resources, Xi'an, Shaanxi 710021, China.  
⁴No.2 Mine, Huangling Mining (Group) Co., Ltd., Huangling 727307, China.  
⁵Ningxia Mine of CHN Energy Investment Group Co., Ltd., Yinchuan 750004, China.

Abstract. Under the action of high-stress field, overlying strata with load characteristics in large space structure formed by changes of working faces in deep mines intensifies the movement of the overlying strata on the working face, which may easily cause dynamic disasters at the working face. Considering the large space structure of deep mines and taking gob-side entry retaining as a breakthrough point, this study analyzes various types of overlying strata structures and their loading effects. The concept and differentiation method of deep “three layers” are introduced. The movement of the overlying strata with loading effect is analyzed by establishing a large-scale Flac3D numerical calculation model and on-site inspection. The results indicate that the “arch” structure formed by the working face shifts to the middle and rear parts of the working face under the influence of the large space structure, and the overlying strata continuously evolves upward during this process. Finally, the “arch” structures of the working face are integrated within the overlying strata to form a symmetrical structure. In the deep “three layers,” “Mk” provides the force source for normal weighing of the working face. “Mj” shifts the stress relief of the working face to the middle–rear position, which may easily cause strong strata pressure at the working face. The uniformly distributed load of “My” ensures the stress relief position at the working face. Through on-site monitoring, the disturbance range and stress of Working Face 418 with large mining height are greater than those of Working Face 416. The changes in pressure relief positions of the working face are as follows: ventilation roadway > middle > intake roadway.

Keywords: deep; large space structure; overlying strata with loading effect; deep “three layers”
1. Introduction

The stress propagation in deep mining changes significantly because of its complex geological structure, which enables the overlying strata to apply loads, thus bringing great challenges to coal mining \(^{1-3}\). The exploitation of deep coal resources has been enhanced to meet the huge demand for energy due to the transformation of major domestic contradictions in the new era. Heavy stress increases with increasing burial depth. Moreover, the overlying strata with different burial depths and lithological properties have certain loads. The static stress of the Working Face 416 fore stoping is affected not only by the overlying strata of the working face but also by the overlying strata of the adjacent working face already mined. Replacing the stope with large mining height forms a “large” spatial structure with large disturbance range and movement space, which may easily cause dynamic disasters at the ventilation roadway. Therefore, the movement of the overlying strata load zone of deep large space structures should be given focus.

Experts and scholars have performed geological surveys, theoretical calculations, numerical calculation, on-site testing, and so on to address practical problems encountered in safe and efficient production in deep mines. Some studies determined the limit depth range and critical point \(^{4-5}\) of deep mining and systematically analyzed the complex mechanical environment of deep “high ground stress, high ground temperature, high karst water pressure, and strong mining disturbance,” the evolution characteristics of engineering disasters \(^{6-7}\), and the unloading failure zone characteristics of rocks with large deformation and arch form \(^{8-9}\). Other studies elucidated different dynamic and static combined loading mechanical mechanisms \(^{10-11}\) and determined the influence of depth on the mechanical behavior of rocks and the energy characteristics and discrimination criteria of dynamic instability \(^{12-14}\). Given the strong disturbance characteristics in deep rock mass mining because of acoustic emission, various characteristics of dynamic tensile specific energy, resistance to compressive deformation, and shear stress of coal rocks under an environment with complex changes were explored \(^{16}\). In addition, a monitoring and early warning system for rock burst in deep coal mines was established \(^{17}\), and the calculation formula of rock mass unloading rate was determined \(^{15}\). With the formation of the large space structure, the fracture and rotation and stress concentration of high-level structure have become complicated. Rock burst largely occurs in the high-stress difference zone \(^{18}\). A technical system \(^{19}\) for the ground–underground and near–far control of hard formation is proposed. The team led by Lai Xingping of Xi’an University of Science and Technology has long been committed to the research on relatively complex coal rock mass. During the shallow-to-deep process of large-section, high-sublevel, fully mechanized top-coal caving mining, the stress transfer, roof failure rule, and overlying rock evolution type were explored through the mechanical parameter determination, mechanical experiments, theoretical analysis, and field monitoring of the surrounding rock; in addition, a roof-weakening scheme for coupled cracking and local deep-hole blasting was proposed to eliminate the causes of dynamic disasters at the fountainhead \(^{20-27}\).

The long-term research on the theories and practices of deep mining has provided strong support for safe and efficient mining. However, relatively few studies focused on the movement of the overlying strata in the deep large space structure. Therefore, considering the results of previous studies on deep stress field, multi-field coupling superposition, strata movement, and other aspects and according to the characteristics of deep stopes with large mining height, this study investigated the movement of the overlying strata in the deep large space structure of the working face with a large mining height in Panel 4 of Huangling No.2 Coal Mine in Shaanxi Province. This study may serve as a basis for the “safe-efficient-scientific” mining of deep stopes with large mining heights.

2. Project Background

2.1 Overview of the coal mine and working face
Located in the middle part of Huanglong Mining Area, Huangling No.2 Coal Mine in Shaanxi Province is the main producing mine, with a production capacity of 8.0 Mt/a. The preliminary survey and exploration results of the mine indicate that with general dip angles of 1° to 5° within the mining range of Panel 4, 2# coal seam is stable to relatively stable, as shown in Figure 1. Within the panel, the surface elevation ranges from +1157 m to +1364 m, the underground elevation ranges from +711 m to +732 m, and the average burial depth is about 530 m. The occurrence of coal seam is characterized by the overlying strata with interlayered fine sandstone and siltstone. A 183.7 m-thick medium sandstone is found in the upper part of the overlying strata. The characteristics of surrounding rock are shown in Table 1.

**Figure 1.** Occurrence conditions of coal seam in Panel 4

**Figure 2.** Column diagram of coal seam

| Name          | Thickness (m) | Characteristics                                                                 |
|---------------|---------------|---------------------------------------------------------------------------------|
| Siltstone     | 7.4 to 15.01  | Semi-hard non-softening rock with a thin layer of silty mudstone, good preparability, Platts hardness f = 6 to 7 and RQD value of about 73.2%. |
| Fine sandstone| 1.12 to 6.19  | Mainly composed of quartz and feldspar, with argillaceous cementation, dotted mica flakes, and dark minerals with wavy bedding, long columnar core, and RQD value of about 56.1%. |
| Mudstone      | 0 to 4.69     | Contains numerous horizontal bedding and small cross bedding, characterized by structural planes such as joints, fissures, and sliding surface. |

Three working faces of 414, 416, and 418 are stoped in sequence. For each working face, the strike length is 2632 m and the inclined length is about 300 m. The average mining heights of Working Faces 414, 416, and 418 are 4.0, 6.0, and 6.0 m, respectively. The safety coal pillar reserved at the working face is 40 m. The dimensions of the intake and ventilation roadways are 4.6 m × 3.8 m and 5.4 m × 3.6 m, respectively. The retreating longwall mining method with full-seam mining is adopted, and Working Faces 416 and 418 use 175 ZYT12000/28/63D supports in total.
2.2 Catastrophe analysis
With one-way mining in the panel, the working faces are generally divided into three types, namely, first mining, GER, and island mining faces (Figure 4). After the first mining face is mined, the unilateral GER of the next working face is formed. Along with the changes in working face, the overlying strata move within a relatively large range. The large space structure is developed by the overlying strata disturbance ranges of the stope with large mining height and GER. During mining, the stress and energy storage of the mining strata vary with time and mining positions, and the released energy level and transfer range increase, which intensifies the development of surrounding rock fissures and may easily result in large floor heave of ventilation roadway and rib spalling at the working face.

The lateral supporting force and surrounding rock movement generated after the mining of the previous working face is stabilized directly affect the static stress and overlying strata movement at the first mining stage. Under the influence of depth, the forces acting on the surrounding rock of the working face vary with the burial depth of rock strata. With the aggravation of mining in the large space structure formed under the conditions of large depth and stope with large mining height and GER, the internal fissures of the overlying strata develop with a high degree of fissure evolution. This phenomenon may easily cause sudden roof instability and generate strong strata pressure. Statistics show that four major dynamic disasters occurred from 2017 to 2019, which damaged the mining system and equipment and seriously restricted safe, efficient, and sustainable mining, as shown in Figure 5.
3.1 Division of deep “three layers”

The large space structure formed by the stope with large mining height and GER is a key factor contributing to dynamic disasters at the working face. Due to large depth, different types of overlying strata have load characteristics, directly causing dynamic disasters at the working face. The combined action of the large space structure and overlying strata with loading effect has a comprehensive time effect, which is the fundamental cause of dynamic disasters at the working face.

The different loading effects of the overlying strata on the working face are referred to as the deep “three layers,” as shown in Figure 6. The mining coal seam consists of the caving layer $M_k$ (Ⅰ), the middle loading layer $M_j$ (Ⅱ), and the far-field layer $M_y$ (Ⅲ) from bottom to top.

Figure 6. Overview of evolution of overlying strata with loading effect in the large space structure

(1) Caving layer ($M_k$): With the advancement of the working face, the roof in the deep well is characterized by periodic movement of “deflection–rupture–rotation–caving” and fills the entire goaf. Along the direction of the working face, the whole caving layer acts on the coal seam and the support. The disturbance stress formed acts on the support and wall, causing rib spalling at the working face.

(2) Middle loading layer ($M_j$): The original rock stress, disturbance stress, and disturbance range in the deep well are relatively large. As the movement range of the caving layer increases and under the action of its own load, the strata become “tough.” The fissures initially developed in the rock strata give rise to the bending and subsidence of the rock strata along with advancing at the working face and, finally, the closing of fissures. Under the action of external load and dead weight, the bending and subsidence of the rock strata cause development and penetration of internal fissures. Therefore, the middle loading layer has the movement feature of “cracking–bending–subsidence–closing.” The formed “arch” structure continuously evolves upward. Affected by the large space structure, the “arch point” moves toward the rear part of the working face and reaches stability. The middle loading layer acts on the caving layer through movement, and a subsidence curve forms on its top, as shown in Figure 5.

(3) Far-field layer ($M_y$): Located far from the working face in the far field, this layer controls the overall strata movement after the movement of other strata. This layer has good continuity toward the surface strata basically under static load. It mainly inhibits surface movement.

3.2 Determination of heights of deep “three layers”

The factors that affect the distribution of the deep “three layers” are mainly related to mining height, burial depth, working face length, and strata properties. The load action of each layer is also different.

(1) Height of caving layer ($M_k$)

After the working face is stoped, a certain space forms in the goaf, and the roof collapses and fills the goaf. The formula for calculation of “caving zone” by Qian Minggao is

$$M = \frac{h}{K-1},$$

where $M$ is the height of the caving zone, $h$ is the mining height, and $K$ is the rock bulking factor, generally with a value ranging from 1.1 to 1.3.
The deep static stress (original rock stress) is relatively large, which increases the stability of the surrounding rock near the working face. After deflection, the roof breaks, rotates, and collapses within a short period of time to form stability within the “caving zone,” where the value of $K$ is 1.2. The height of the caving layer is calculated as shown in Formula (2).

\[ h = M \approx 5h \]  

(2) Height of far-field layer ($M_f$)

According to the distribution characteristics of strata, the key layer in the far field is determined. The height of the far field layer $M_f$ is equal to the height from the far-field key layer to the surface.

(3) Height of middle loading layer ($M_j$)

Under the action of its own load, its internal evolution is complicated. According to the definition of the middle loading layer, with the temporal and spatial changes of mining, it reaches the fracture limit under load, giving rise to delamination and fracture. Its height can be calculated as follows:

\[ M_j = H - M_k - M_y \]  

The height of the middle loading layer ($M_j$) is determined by the buried depth ($H$) and the height of the caving layer and far-field key layer.

3.3 Numerical modeling

According to the occurrence characteristics of the rock strata in Panel 4 of No.2 Coal Mine as shown in Figure 7, The initial stress of the coal seam is about 13.2 MPa. The model has dimensions of $1500 \times 550 \times 570$ (m), with 298,962 nodes and 286,700 grids. With all sides and the bottom unchanged, the working face is simulated toward the average surface. Three working faces (414, 416, and 418) are designed in the model, with 200 m and 320 m high boundary coal pillars and a 40 m high safety coal pillar. The model is divided according to the deep “three layers,” and the Mohr–Coulomb criterion is adopted.

Table 2. Mechanical parameters of surrounding rock

| Name          | Bulk modulus /GPa | Shear modulus /GPa | Tensile strength /MPa | Cohesion /MPa | Internal friction angle /° | Bulk density /kg.m$^{-3}$ |
|---------------|-------------------|--------------------|-----------------------|---------------|---------------------------|--------------------------|
| Siltstone     | 7.35              | 5.03               | 6.80                  | 5.72          | 31                        | 2700                     |
| Fine sandstone| 5.16              | 4.21               | 5.50                  | 4.9           | 27.5                      | 2650                     |
Three working faces (414, 416, and 418) are excavated in sequence to analyze the movement of the overlying strata in the deep GER stope with large mining height. The heights of the deep “three layers” ($M_k$, $M_j$, and $M_y$) are about 30, 260, and 210 m, respectively, and the far-field key layer is composed of 183.7 m-thick medium sandstone. Segments are taken for 260 m along the Y direction of the calculation model to analyze the movement of the overlying strata under continuous changes of working faces.

4. Analysis on Evolution of Overlying Strata with Loading Effect

4.1 Mining characteristics of Working Face 414

Working Face A is the first mining face, and the disturbance of the entire overlying strata basically presents a symmetrical structure, as shown in Figure 8.

Shear failure is mostly observed in the strata at both ends of the working face, and yield failure also exists in the strata at the end of the working face. The failure boundaries of the overlying strata are 77° and 72°. The immediate roof collapsed directly under the action of shear failure along with the extraction of coal seam. The $M_j$ layer with a vertical distance of about 38 m from the working face reaches the yield limit and collapses and acts on the $M_k$ layer. As a result, both ends of the roof of the working face reach the shear resistance limit, causing overall caving. The $M_y$ layer is generally intact.

4.2 Mining characteristics of Working Face 416

After the stoping of B, the first GER working face reaches stability, and the overall plastic failure of the overlying strata is shown in Figure 9.

Affected by Working Face A, the disturbance of the overlying strata becomes severe after Working Face 416 is mined. The $M_j$ layer near the working face suffers from tensile failure in the middle and rear sections of Working Face 416, and the top of the “arch” structure inclines toward the rear end of the working face. The 160 m position at the $M_j$ layer has shear failure. Tensile damage occurs at the bottom of the $M_j$ layer. With the continuous upward evolution of “arch” and its connection with working face A, symmetrical “arch” plastic failure occurs.
inside the overlying strata. Shear failure mostly occurs at both ends of the working face and its overlying rock, with the failure boundary of about 60°. According to the division of the overlying strata with loading effect, the disturbance characteristics of each loading layer are as follows:

(1) Disturbance characteristic of $M_k$
Along with the stoping of the working face, the fine sandstone near Working Face 418 collapsed. Due to its high strength and certain bearing capacity, “$M_k$” siltstone forms roof overhang. The stress distribution characteristics of siltstone at the layer are extracted, as shown in Figure 10.

![Figure 10](image1.png)

**Figure 10.** Distribution characteristics of disturbance stresses of $M_k$ siltstone

After the first GER working face is formed, all siltstones in the upper part of Working Face 418 collapse, resulting in weighting of the working face. With the caving of the rock strata, the lateral stress shifts to the direction of the intact coal seam, and a large amount of energy accumulates within the coal seam, with the peak value being about 40 m away from the working face. The peak stress of coal pillar is basically equal to the peak lateral stress.
Comparing the above two working faces, the disturbance stress at the end of Working Face 416 is not completely released, with higher energy storage. With the advancing at the working face, the roof at the end of the working face is prone to develop long-distance roof overhang, causing strong strata pressure in the ventilation roadway.

(2) Disturbance characteristics of $M_j$
The $M_j$ layer loses support after the $M_k$ layer collapses and deforms under the combined action of its dead weight and “$M_j$” layer. The original rock stresses of 95 and 185 m fine sandstones are about 9.8 and 7.5 MPa, respectively, and the bearing stress boundary is 10.29 MPa and 7.875 MPa respectively. The stress distribution characteristics of fine sandstones at 95 and 185 m away from the working face in this layer (one mark every 15 m) are extracted respectively, as shown in Figure 11.

![Figure 11](image2.png)

**Figure 11.** Distribution characteristics of disturbance stresses of “$M_j$” fine sandstones
The $M_j$ original rock stress and disturbance stress in the overlying strata are less than those of the $M_k$ layer. The fine sandstones in the upper part of the working face apply different loads on the roof. At 95 m, the lowest stress relief zones are at about 30 m away from both sides of the coal pillar of the working face of the fine sandstones. The ranges of lowest stress relief
zones of A and B working faces are about 60 and 120 m, respectively. At 185 m, the stress value of the fine sandstone pressure relief zone is 0 MPa with a small deviation. Along with advancing, energy is stored at the end of the working face.

| Name | Peak value MPa | Ratio against original rock stress/MPa | Distance of peak value from the wall/m | Difference between maximum and minimum values/MPa |
|------|----------------|----------------------------------------|---------------------------------------|-----------------------------------------------|
| 95 m | 24.3           | 2.37                                   | 40                                    | 25.54                                         |
| 185 m| 10.4           | 1.32                                   | 70                                    | 9.76                                          |

The variation characteristics of the disturbance stress of the \( M_j \) layer in the overlying strata with loading effect in the deep large space structure are shown in Table 3. The fine sandstones at 95 m are affected by caving of the \( M_k \) layer, and its movement is apparently intense. After two groups of fine sandstones are disturbed, the overlying strata form superposition of the disturbance stresses from top to bottom, acting on the \( M_k \) layer. Therefore, the load from the \( M_j \) layer controls the movement of the \( M_k \) layer, and the energy release gives rise to “vibration” in the overlying strata. Strong strata pressure is generated in the middle and rear parts of the working face.

(3) Disturbance characteristics of \( M_y \)

The far-field key layer features large thickness and high stability compared with other layers. Its original rock stress is about 3.9 MPa, and the bearing stress boundary is about 4.095 MPa. The disturbance stress characteristics (one mark every 15 m) at 150 m from the simulated surface (about 350 m from the working face) are extracted, as shown in Figure 12.

![Figure 12](image)

**Figure 12.** Distribution characteristics of disturbance stresses of \( M_y \) sandstone

After the coal seam is extracted, the overlying strata is disturbed from bottom to top, and the sandstone in the \( M_y \) layer shows a gentle “V” type distribution feature, having a disturbance range of 4.6 MPa to 1.55 MPa, with a deviation of 3.05 MPa. The results indicate that the disturbed \( M_y \) layer exerts its dead weight on the \( M_j \) layer evenly and reaches stability, thereby effectively restraining stress transmission, preventing surface movement, and ensuring that the load from the \( M_j \) layer is applied to the middle and rear parts of the working face.

4.3 Mining characteristics of Working Face 418

With the gradual increase in large space, the movement of the overlying strata is further intensified. The plastic failure of the entire overlying strata after the stoping of Working Face 418 has reached stability is shown in Figure 13, which is similar to the failure type of Working Face 416. The changes in working faces expand the movement space of the overlying strata, and the overlying strata disturbance of Working Face 418 is more severe than those of the other work faces, with more intense movement of the overlying strata.
Shear failure mostly occurs in the current working face and at both ends of the mined coal seam. After Working Face 418 remains stable during mining, the resulting “arch” structures generated by the overlying strata of 414, 416, and 418 working faces move toward the alternation direction, middle part, and end of each working face, respectively, and the overlying strata generally presents symmetrical “arch” plastic failure. The evolution boundary of overlying strata at both ends of the working face is about 60°.

After the above three working faces remain stable during mining, the disturbance stress values of observation points of the deep “three layers” are extracted, with disturbance characteristics as follows:

1. Disturbance characteristics of $M_k$
   The mining area of the panel is enlarged, and the “Mk” disturbance stress is shown in Figure 14.

   Figure 13. Stopping characteristics of Working Face 418

   After Working Face 418 remains stable during mining, the peak stress, which is greater than 40 MPa, appears in the middle part of the safety coal pillar. A peak stress of about 29.34 MPa occurs about 40 m from the wall. The range of pressure relief zone is about 240 m at the middle part of the working face.

   The $M_k$ layer collapses and acts directly on the support of the working face. The stress is relatively concentrated within 10 m from the end of each working face, and the accumulated energy cannot be released in a timely manner, which may easily cause ultra-long roof overhang and bending and subsidence of roof of the working face. The ventilation roadway in this study is prone to caving and large-area floor heave.

2. Disturbance characteristics of $M_j$
   After the mining of Working Face 418, the stress disturbance of fine sandstones at 95 and 185 m above the working face is shown in Figure 14. Fine sandstones at 95 m in the upper parts of 414, 416, and 418 show the characteristic of “U”-type stress relief. The lowest stress relief zone of each working face shifts to the right, middle, and left, respectively. The pressure at the 900–1050 m (150 m range at the middle and rear parts of the working face) range of Working Face 418 is relatively high.

   Affected by the horizon, the peak stress at the upper part of the coal pillar is smaller than the lateral support stress. The peak value of the lateral bearing stress of Working Face 418 is about 24.87 MPa, which is about 40 m away from the boundary of the working face. The disturbance stress at 185 m in the upper part of the working face is distributed symmetrically.
in a “concave” shape. The pressure relief zone extends from 215 m to 1135 m at the working face, with stress values basically around 0 MPa.

![Figure 15](image)

**Figure 15.** Distribution characteristics of disturbance stresses of $M_f$ fine sandstone

After caving of the $M_k$ layer, the disturbance stresses of the $M_f$ layer have two distribution features. One is that the strata with loading effect near the working face, affected by GER, applies external load to the $M_k$ layer within a range of about 150 m at the middle–rear part of the working face, whereas the stress of the coal pillar increases with the increase in the large space. The other is that as the $M_f$ layer is higher, the distribution of disturbance stresses is symmetrical, with small relative stress relief. Therefore, the different stress relief conditions of the $M_f$ layer control the deflection degree of the $M_k$ layer and the distribution of disturbed stresses at the working face and widely act on the plastic zone concentrated area of the $M_k$ layer, which may easily cause “shock bump” and dynamic disasters at the working face.

(3) Disturbance characteristics of $M_r$

The stress distribution of the far-field layer presents a “concave” type after Working Face 418 remains stable during mining. Compared with the lateral stresses of the other two layers, it has the smallest range of about 15 m, as shown in Figure 16. After disturbance, the stress of each monitoring point remains stable, with a value greater than 1 MPa. The load of the layer is applied evenly on the $M_f$ layer to provide the desirable stress relief characteristics of the $M_f$ layer and restrain upward evolution of strata movement and prevent surface movement. The $M_f$ layer controls strata movement and ensures the stress relief positions at the working face.

![Figure 16](image)

**Figure 16.** Distribution characteristics of disturbance stresses of $M_k$ sandstone

### 5 Field Validation

#### 5.1 Borehole peeping inspection

The YZT-II rock drilling detector is adopted at the site. The detection is carried out vertically upward at 5 m in front of the upper corner of Working Face 418, with an effective detection height of 35 m. Images at detection depths of 1, 5, 10, 15, 23, and 30 m are captured, as shown in Figure 17.
Cracks are developed within the 10 m range of the roof, and the roof strata are relatively crushed, as shown in Figure 16(a). Small separation layers and through fissures appear at 15 and 23 m, one through fissure and small separation layers exist at 15 m, and the strata fissure continues to evolve upward at 30 m, as shown in Figure 16(b). Under the disturbance of coal seam mining, the $M_k$ layer moves violently with a height of about 30 m, which is the direct source of weighting for the working face. Under the action of overlying layer with loading effect (i.e., “$M_j$”), the upward evolution of roof fissures is intensified, which acts on the $M_k$ layer, thus easily causing dynamic disasters at the working face.

5.2 Pressure detection of support
The support adopts the SAC electro-hydraulic control system to automatically monitor the working condition of the support during advancing at the working face. The setting load of the support is set to 27.5 MPa. Statistics are made on the support working resistance of Working Face 416 from January to February and Working Face 418 in January. Affected by Working Face 414, the pressure distribution of Working Face 416 from January to February is shown in Figure 18.

The weighting range of Working Face 416 is mainly at the middle part of the working face (45#–100#), of which 70#–90# is the position of continuous weighting, with a value range of 43.6–52.1 MPa. After 35 days of continuous advancing and mining, 115#–132# has pressure concentration, with a value range of 41.7–47.8 MPa. Number of pressure distribution positions: middle > ventilation roadway > intake roadway.

After the large space structure is developed, the support working resistance is shown in Figure 19 during continuous advancing and mining of Working Face 418.
Figure 19. Overview of pressure distribution at Working Face 418

The overall pressure of the working face is relatively high, which mainly exists between 55# and 155#, of which 110#–155# (Zone 1) and 55#–100# (Zone 2) have relatively concentrated weighting. Number of pressure distribution positions of the working face: ventilation roadway > middle > intake roadway. The pressure at the tail is large and relatively continuous. The weighting of 7#–12# lasts for a long time, with the pressure value range of 45.3–55.7 MPa.

The pressure of Working Face 418 in the large space structure shifts to the tail, with large pressure value and large disturbance stress range. Therefore, the “Mk” layer is the source of normal weighting for the working face. “Mj” controls the deflection degree of the “Mk” layer of the working face and the stress distribution, resulting in strong strata pressure of the working face.

6. Conclusion

(1) On the basis of the analysis of the occurrence conditions of the overlying strata at the working face, the concept of deep “three layers” is proposed according to the spatial position, thickness, and load characteristics of each layer. The discrimination method and heights of deep “three layers” are also confirmed. The heights of deep “three layers” (Mk, Mj, and My) of the large mining height working face in Panel 4 are about 30, 260, and 210 m, respectively.

(2) The large space structure generates an “arch” structure at the working face, which shifts to the middle and rear parts of the working face. During this process, the overlying strata continuously evolves upward and merges with the “arch” structures developed at other working faces, finally forming a symmetrical “arch” structure.

(3) Shear failure is mostly seen in the overlying strata under disturbance. Among the deep “three layers,” “Mk” is the source of weighting for the working face. “Mj” controls the deflection degree of “Mk” and shifts the stress relief of the working face changes to ventilation roadway position. The uniformly distributed load of “My” controls the movement of the rock strata and ensures the stress relief positions at the working face.

(4) Through on-site monitoring, the disturbance range and stress value of Working Face 418 are greater than those of Working Face 416 in the large space structure. The changes in pressure relief positions of the entire working face are ventilation roadway > middle > intake roadway.

References

[1] Cai MF, Edwin T. Brown. Challenges in the Mining and Utilization of Deep Mineral Resources[J]. Engineering, 2017.4:432-435.
[2] Pathegama G. Ranjith, Jian Zhao, Minghe Ju, et al. Opportunities and Challenges in Deep Mining: A Brief Review[J]. Engineering,2017,3:546–551.
[3] Teng JW, Qiao YH, Song PH. Analysis of exploration,potential reserves and high efficient utilization of coal in China[J]. Chinese Journal of geophysics.2016, 12(59):4634-4654.
[4] Xie HP, Zhou HWi, Xue DI, et al. Research and consideration on deep coal mining and critical mining depth[J]. Journal of China Coal Society.2012,4(37):536-543.
[5] Zhang JM, Li QS, Zhang Y, et al. Definition of deep coal mining and response analysis[J]. Journal of China Coal Society.2019,44(5):1314-1328.
[6] Xie HP. Research review of the state key research development program of China:Deep rock mechanics and mining theory[J]. Journal of China Coal Society.2019,44(5):1283-1305.
[7] He Manchao, Xie Heping, Peng Suping, et al. Research on Rock Mass Mechanics in Deep Mining[A]. Proceedings of the 4th Deep Rock Mechanics and Engineering Disaster Control Symposium[C]. Beijig,2009.
[8] He MC. Progress and challenges of soft rock engineering in depth[J]. Journal of China Coal Society.2014, 39(8):1409-1417.
[9] Li CY, Zhang Y, Zuo JP, et al. Floor failure mechanical behavior and partition characteristics under the disturbance of voussoir beam instability in deep coal mining[J]. Journal of China Coal Society.2019,44 (5):1508-1520.
[10] Li XB, Gong FQ, Wang SF, et al. Coupled static-dynamic loading mechanical mechanism and dynamic criterion of rockburst in deep hard rock mines[J]. Chinese Journal of Rock Mechanics and Engineering. 2019,38(4):708-724.
[11] Li XB, Li CJ, Cao WZ, et al. Dynamic stress concentration and energy evolution of deep-buried tunnels under blasting loads[J]. International Journal of Rock Mechanics and Mining Sciences,2018,104:131-146.
[12] Li LY, Xie HP, Ju Y, et al. Experimental study on the release of strain energy and dissipated energy from rocks [J]. Engineering Mechanics, 2011,28(3):35-40.
[13] Cai MFg, Ji D, Guo QF. Study of rockburst prediction based on in-situ stress measurement and theory of energy accumulation caused by mining disturbance[J]. Chinese Journal of Rock Mechanics and Engineering,2013,32(10):1973-1980.
[14] Li PB, Wang JN. Experimental study on mechanical properties of overlying strata in coal seam with variation of occurrence depth [J]. Journal of Harbin Institute of Technology, 2015, 47(12):98-101.
[15] Peng RD, Xue DJ, Sun HF, et al. Characteristics of strong disturbance to rock mass in deep mining[J]. Journal of China Coal Society.2019,44(5):1359-1368.
[16] Zhang LJ, Cai MF, Lai XP, et al. Dynamical destabilization analysis of steep and heavy thick coal seam in a deep-mine under the complex-variable environment based on AE[J]. Journal of University of Science and Technology Beijing.2007,29(1):1-5.
[17] Jiang YD, Pan YS, Jiang FX, et al. State of the art review on mechanism and prevention of coal bumps in China[J]. Journal of China Coal Society.2014,39(2):205-213.
[18] Jiang FX,Wang JC,Sun GJ,et al.Engineering criterion of gob-side entry rock burst hazard in deep mining[J].Journal of China Coal Society.2015,40(8):1729-1736.
[19] Yu B, Gao R, Meng XB, et al. Near-far strata structure instability and associate strata behaviors in large space and corresponding control technology[J]. Chinese Journal of Rock Mechanics and Engineering, 2018, 37(5): 1134-1144.

[20] Cui F, Lai XP, Chen JQ, et al. Application of Coupled-Cracking Technology in Inclined and Extra-Thick Coal Layer[J]. China J. Rock Mech. Eng. 2015;34(8):1569-1580.

[21] Cui F, Lai XP, Cao JT, et al. Intact-loose Medium Equivalent Transformation After Coupled Cracking and Assessment of Caving Capability[J]. China J. Rock Mech. Eng. 2015;34(3):565-571.

[22] Shan PF, Lai XP, Mesoscopic structure PFC2D model of soil rock mixture based on digital image[J]. J. Vis. Commun. Image R. 2019; 58: 407–415.

[23] Shan PF, Lai XP, Influence of CT scanning parameters on rock and soil images[J]. J. Vis. Commun. Image R. 2019;58 :642–650.

[24] Shan PF, Lai XP, Liu X M. Correlational analytical characterisation of energy dissipation-liberation and acoustic emission during coal-rock mass fracture inducing by coal excavation[J]. Energies, 2019, 12(12), 2382.

[25] Lai XP, Shan PF, Cao JT, et al. Hybrid assessment of pre-blasting weakening to horizontal section top coal caving (HSTCC) in steep and thick seams[J]. International Journal of Mining Science and Technology 2014,24(1): 31-37.

[26] Lai XP, Li YP, Wang NB, et al. Roof deformation characteristics with full-mechanized caving face based on beam structure in extremely inclined coal seam[J]. J. Min. Saf. Eng. 2015;32(6):873-878.

[27] Lai XP, Lei ZY, Li Z. Comprehensive analysis of roof migration characteristics of top-caving roof in extremely steep and thick coal seams[J]. Journal of Xi'an University of Science and Technology, 2016, 36(5): 609-615.