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A New Calculation Method of Hydraulic Support Type for 14022 Working Face Combining Fully-Mechanized Mining with Caving in Zhaogu Mine

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Abstract: When the working face combining fully-mechanized mining with caving is advancing, the strata behavior and ground pressure at the junction of the fully-mechanized caving area and the fully-mechanized mining area is quite different from that of the ordinary fully-mechanized mining or fully-mechanized caving condition. Reasonable hydraulic support selection can effectively reduce the occurrence of production safety accidents in a mine. This paper focuses on the 14022 working face combining fully-mechanized mining with caving at the Zhaogu No.2 Mine. The support resistance is estimated to be no less than 8746.7 kN. Based on structural modeling and calculation methods, the analysis of surrounding borehole columns 13152 and 7037 using “cantilever beams” and “masonry beams” structures determines that the support resistance should be at least 9260.1kN. After comparing the results, the hydraulic support model for the comprehensive excavation and cutting area of working face 14022 is determined to be ZF10000/20/32D (Intermediate Support), ZFG10000/20/32D (Transitional Support), and ZFG10000/22/35D (End Support).

Keywords: Fully-mechanized mining, Fully-mechanized caving, calculation method, Support resistance, Support selection.

I. Introduction

According to academician Xie Heping (2015)[1-3] under the energy situation of "scarce oil, gas and abundant coal" in China, the country continues to rely heavily on coal resources in its energy structure in a long term. As the mining capacity of coal mines continues to increase and shallow coal resources become increasingly exhausted, deep mining becomes normally in China. As a result, the problem of increased stress and abnormal ground pressure arises in deep mining. Among the many issues faced in deep mining, the roof problem is the main challenge in controlling the strata pressure of mining operations. This is especially true when using fully-mechanized systems for combining fully-mechanized mining with caving, where the strata pressure at the intersection between fully-mechanized mining with caving areas differs significantly from the pressure encountered in traditional mining model. However, suitable selection of hydraulic supports can effectively reduce the occurrence of roof caving and coal wall collapse, allowing hydraulic supports to fully demonstrate their performance, which improves mine production safety, reduces mining costs, and increases production efficiency.

Currently, there are many reference formulas for selecting and designing hydraulic supports, most of which are based on the mechanics models of "masonry beams" and "cantilever beams" proposed by academician

Qian Minggao (1996)[4-6], as well as the "key strata theory" for estimating the roof pressure. In addition, Song Xuanmin et al.(2021)[7] proposed the dynamic evolution law of the roof structure of a mining area based on the premise of stabilizing the "support-rock" system under various strong ground pressure conditions, while Guo Wenbing et al. (2019)[8] studied the fully extracted characteristics of overlying strata failure under high-intensity mining, revealing that as the mining depth increases, problems such as roof caving, coal wall collapse, and deformation of adjacent roadway become more apparent. Meng Zhaosheng et al.(2017)[9] divided hydraulic supports into single-zone and hyperbolic bearing types, and constructed support capacity models for the hydraulic supports in both configurations. Shi Yuanwei et al. (1999)[10]summarized the results of laboratory and field tests on the mechanical interaction between hydraulic supports and surrounding rock in long wall mining, and discussed the control effects of different support structures on the roof and floor, as well as the selection criteria of support structures. Additionally, Li Huamin et al.(2017)[11] analyzed the movement of overlying strata, strata pressure, and support resistance during high-intensity mining at the Dalitang coal mine, and concluded that the stress amplitude of the top beam of hydraulic supports can be used to determine the state of support compression and the degree of violent overlying strata failure.

The ability of hydraulic supports to provide adequate support is the foundation for ensuring safe mining operations[12].Research on strata pressure and corresponding support resistance calculations during combined cutting and rock removal operations is relatively sparse in China. In this paper, the hydraulic support selection of the 14022 working face combining fully-mechanized mining with caving at Zhaogu No.2 mine is taken as an example, and the drill column chart and the key layer position are analyzed. Based on these fundamental data, the paper uses both the empirical estimation method and structural model calculation method to comprehensively determine the hydraulic support model, which provides references for the roof control and support selection of deep combined cutting and rock removal faces in the future.

II. Coal Seam Condition and Working Face Design

2.1Coal seam situation of 14022 fully mechanized mining face

Coal seam characteristics and 14022 working face design locating at the western part of the mine are summarized as follows: trend 181°～261°, dip angle 3.2°～6.8°, simple structure, single coal type, stable layer position, mainly black block bright coal with developed endogenous fissures, some fissures are filled with calcite, and local thin-layered gangue and a small amount of pyrite are contained. According to the drilling construction situation of the roof separating layer working face and the actual exposed data underground, the roof and floor conditions of the coal seam in the working face are shown in Table 1.

Table 1: Coal seam roof and floor condition

Stratum name	Thickness /m	Description of the rock
Immediate roof	11.75	Sandy shale and shale, stable
Upper roof	6.0～7.0	Mostly quartz and feldspar, relatively weak
Immediate bottom	13.73～14.04	Sandy shale and shale, expansion when exposed to water
Old bottom	0.95～1.36	L9 limestone containing fossilized animals, dense, hard

2.2 Working face parameter design

Design volume of 14022 working face is 3516.3m at the elevation of -639.6～-691.4m. During excavation, the thickness of the coal seam in the bottom separating layer segment is 1.3-3.5m, while in the coal column segment it is 5.1-6.4m. The lower-layer fully mechanized caving process is used for the lower separating layer coal body that has already been mined, while the fully mechanized caving process is used for the unmined edge coal column segment in the upper separating layer. This is a synergistic mining method combining fully-mechanized caving and top-coal caving on the same working face.Press-in ventilation method is applied during the excavation process

III. Calculation for selecting hydraulic supports

To ensure that the selected hydraulic support meets the requirements of the fully mechanized mining section, the calculation of working resistance of the hydraulic support in the coal pillar section is carried out using both empirical estimation method and structural model calculation method.

3.1 Empirical estimation method

Using empirical formulas to estimate the strength of support.

In the formula: Q——support strength, MPa;

n——The ratio of overlying strata thickness to mining height for working face support;

γ——Roof rock bulk density, 25kN/m^3;

M——Maximum thickness of coal pillar, 6.4m.

The roof of the working face is medium to hard rock with good stability, calculated by 8 times the mining height:

$$Q = n \times \gamma \times M = 1.28\text{MPa}$$

The selection of hydraulic supports in the fourth panel area of Zhaogu No.2 mine requires a controlled roof surface area of 6.15 square meters, based on a controlled roof distance of 4.1 meters and a hydraulic support width of 1.5 meters.

The resistance of the support is:

$$F = \frac{QS}{\eta} = 8746.7\text{kN}$$

In this formula: F——resistance of the support, kN;

S——supported area of the hydraulic support, taken 6.15 m^2;

η——operating efficiency of the hydraulic support, taken 0.90.

To sum up, according to the empirical estimation method, the calculated working resistance of the hydraulic support should not be less than 8746.7 kN.

3.2Structural model calculation method

The manifestation of strata pressure in the working face is caused by the movement of the overlying strata due to the mining-induced strata failure. The intensity of the manifestation is related to the movement characteristics of the overlying strata structure. The occurrence state of the key strata in the overburden and the structural form formed after the fracture affects the mine pressure appearance of the working face. The key layer in the overlying strata is located in the "three zones" mentioned above, which determines the structural form that can be formed when the key layer breaks. In the gob caving zone of the fully mechanized mining face, the height of the gob is relatively large. The key layer that can form a hinged equilibrium structure in the general mining height may not be able to form a stable masonry beam structure due to the large turning angle when the mining height is relatively large. Instead, it directly collapses in a cantilever beam structure. The key layer at a higher stratum position can form a stable masonry beam structure by hinging.

3.2.1 The height of gob caving zone

Firstly, it is necessary to calculate the height of the gob caving zone according to the theory of rock fragmentation coefficient and analyze the structural form formed after the overlying strata failure. The calculation of the height of gob caving zone is as follows:

$$h_C = \frac{M}{K_p - 1}$$

In this formula: M——thickness of the coal pillar, m;

K_p——The rock fragmentation coefficient, 1.2.

Substituting the coal thickness values of 6.03m for borehole #13152 and 6.65m for borehole #7307 into the formula, the resulting gob heights are 30.15m and 33.25m.

3.2.2 Calculation of structural models

Based on the cylindrical structure of borehole #13152, the calculation of the structural model can be carried out.

The structural form of the key layer can be determined by the turning angle of the broken blocks. The sandy mudstone located below the sub-key layer 1 directly enters the gob during the mining process due to poor rock stability.

(1) The calculation of the available turning angle Δ of rock blocks in the key layer

The available turning angle Δ of rock blocks in the key layer is the spatial displacement of the key stratum and the directly overlying stratum below after fragmentation and compaction:

$$\Delta = \sum h + M - K_P \sum h - M_1(1 - 0.90)K_{P1} = 2.1824\text{m}$$

In this formula:Σh——immediate roof thickness,17.3m;

M——thickness of the coal pillar,6.03m;

M_1——Top coal thickness in fully-mechanized caving mining,3.23m;

K_P——The fragmentation coefficient of the immediate roof,1.2;

K_{P1}——The coal fragmentation coefficient,1.2;

0.90——The recovery rate of top coal.

(2) Calculation of ultimate torsion limit of key strata

The ultimate torsion limit of key stratais the maximum amount of rotation and subsidence that forms a stable hingestructure of the broken key strata block.

$$\Delta_{max} = h - \sqrt{\frac{2ql^2}{\eta\sigma_c}} (1)$$

In this formula:

h——The thickness of the key strata,2.82m;

q——The load on the key strata and overlying layers;

l——The fracture step distance of the key strata,18;

η——The compression coefficient of the broken rock blocks in the corner of the key strata rupture, generally taken as 0.4;

σ_c——The compressive strength of the broken rock blocks in the key strata rupture,42MPa.

Regarding the load on the key strata and overlying layers, if the load on the neighboring key strata above is not considered as an additional load on this layer's key strata, then the load on the key strata and overlying layers is:

$$q = \gamma(h + h_1)(2)$$

In this formula:

γ——The bulk density of the rock strata, 25kN/m^3;

h_1——The thickness of the rock between two key strata,11.18m.

By solving equations (1) and (2) with the given data, the ultimate torsion limit of key strata is 0.28m.

(3) The determination of the key strata structure

If the available rotation amount of the key strata block is greater than its ultimate torsion limit, the key strata enters the collapse zone and take on cantilever beam structure. Conversely, if the available rotation amount of the key strata block is less than or equal to its ultimate torsion limit, the key strata enters the fracture zone and form stablehinge structure.

Subkey stratum 1 is located in the collapse zone, with $\Delta > \Delta_{max}$, forming a cantilever beam structure. Similarly, subkey stratum 2, composed of sandy mudstone, can form a stable masonry beamstructure.

(4) Determination of the height of the collapse zone

By assessing the structure of the key layer, it can be inferred that the subkey layer 1 is located in the collapse zone. Based on the geological drilling structure of 13152, the height of the collapse zone can be determined to be 24 m after the coal seam is excavated on the working face.

(5) Calculation of working resistance of hydraulic support

Based on the above analysis, the key layer features a structure comprising of a cantilever beam and a masonry beam. As such, the working resistance of the hydraulic support should be calculated in two parts. The first part of the calculation is the weight of the rock layers in the collapse zone. The load Q_Z from the direct roof of the subkey layer 1 is calculated based on the control distance of the hydraulic support. Meanwhile, the weight of the rock layer Q_0 from subkey layer 1 to the top boundary of the collapse zone is calculated based on the suspended length of subkey layer 1. The load P_{H1}required for the control of the fractured zone rock layer is calculated using the formula for the masonry beam structure theory.

$$P = Q_Z + P_H + Q_0 \tag{3}$$

$$Q_Z = bl_k \sum h\gamma_z \tag{4}$$

$$L = l_k + \sum h_1 cot\alpha \tag{5}$$

$$Q_0 = BbLh_1\gamma_z \tag{6}$$

$$P_{H1} = b\left[2 - \frac{L_1 \tan(\phi - \alpha)}{2(h - \boldsymbol{\Delta})}\right]Q \tag{7}$$

In this formula:

P——Working resistance of the hydraulic support;

b——Center distance of the hydraulic support,1.5m;

lk——Roof-control distance,4.1m;

Σh——Immediate roof thickness, 20.53m;

γ_z——The bulk density of the immediate roof,25kN/m^3;

L——The breaking distance of cantilever beam, m;

Σh_1——Thickness of underlying rock layers of the cantilever beam, 20.53m;

α——The angle of fracture of the immediate roof, cotα=0.57;

h_1——The thickness of the key inter-layer stratum varies across layers, 6.7m;

L_1——key stratum periodic weighting distance, 18m;

P_{H1}——Pressure on hydraulic supports by masonry beam structures, kN;

φ——Angle of friction between rock blocks, tanφ=0.8;

Δ——Amount of subsidence of key layer fractured rock blocks, m;

Q——Self-weight of key layer, KPa.

By simultaneously solving equations (3), (4), and (5), the shear span of cantilever beam is determined to be 15.8 m, with a direct vertical load of 2937.98kN and an overburden load of 3970.28kN.

The rock formations above the gob can form a masonry beam structure, and the fracture distance is compressed by the cycle of 18 m. The key layer 1 forms a masonry beam structure, which means that the rock formation enters the fissure zone, where the fragmentation coefficient of the rock formation is significantly lower compared to the overlying gob. The fragmentation coefficient of the sandstone mud-stone is taken as 1.1. Firstly, consider whether the 1.36m fine sandstone can form an equilibrium state:

$$\Delta = \sum h + M - K_p \sum h - M_1(1-0.90)K_{P1} = 0.212$$

$$q = \gamma(h + h_1) = 182.5\text{KPa}$$

$$\Delta\text{max} = h - \sqrt{\frac{2ql^2}{\eta\sigma_c}} = 3.288\text{m}$$

$$P_{H1} = b\left[2 - \frac{L_1\tan(\phi - \alpha)}{2(h - \Delta)}\right]Q = -3921.7\text{kN}$$

Given that P_{H1} is negative in the above equation, it implies that the 1.36m thick fine sandstone can attain a state of equilibrium on its own without requiring any supplementary support forces from the hydraulic support to maintain stability.

Similarly, for the 5.94m thick sandstone mud-stone, the fracture distance is compressed under a cycle of 18m. The sinking amount of the key layer fractured rock block Δ is around 1.5124m. The required additional force for the hydraulic bracket is 1498.9kN.

Hence, the supporting resistance of the hydraulic bracket can be calculated as follows:

$$P = Q_Z + P_H + Q_0 = 8407.16\text{kN}$$

Based on the 13152 borehole data and using a structural modeling calculation method, it is determined that the working resistance of the hydraulic bracket should not be lower than 8407.16kN.

Similarly, by following the same steps and utilizing data from borehole 7307, the working resistance for the hydraulic bracket should not be lower than 9260.1kN.

IV. Conclusion

This paper utilizes the field drilling column diagram to calculate the working resistance of the hydraulic bracket for the 14022 working face of Zhaogu No.2 mine through various analytical methods. After a comparative analysis, the optimal support type is determined, and the following conclusion is drawn.

Firstly, in order to maximize the economic and technical effects of the fully mechanized caving mining area of 14022 working face in Zhaogu No.2 mine, the working resistance of 10000 kN support can meet the support requirements. The selection of hydraulic support is ZF10000/20/32D (middle section), ZFG10000/20/32D (transition section), and ZFG10000/22/35D (end section).

Secondly, the rock pressure law is influenced by the geological structure and key layer conditions. The mining face of the same coal seam and adjacent coal seams exhibits similar rock pressure laws. Therefore, it can provide reference for the support resistance of the current working face based on the measured results of rock structure and mine pressure near the working face.

Thirdly, the working face combining fully-mechanized mining with caving can liberate a large number of coal resources left in the coal pillar position and improve the resource recovery rate. However, the ground pressure behavior at the junction of fully mechanized caving area and fully mechanized mining area is quite different from that of ordinary mining model. This paper can provide anew calculation method of hydraulic support type for 14022 working face combining fully-mechanized mining with caving in Zhaogu mine.

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