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Research Article

Research on the Movement Law of Roof Structure in Large-Inclined Coal Seam Working Face: A Case Study in Liu.Pan.Shui. Mining Area

Haidong Zhang ,[1,2] Guozhong Hu,[1,3] and Guangchen Zhao[2]

[1]*School of Mines, China University of Mining and Technology, Xvzhou 221116, China*
[2]*Department of Civil and Construction Engineering, Shanxi Institute of Technology, Yangquan 045000, China*
[3]*Key Laboratory of Deep Coal Resources Mining of Ministry of Education, China University of Mining and Technology, Xvzhou 221116, China*

Correspondence should be addressed to Haidong Zhang; haidongzhang221116@163.com

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In the Liu.Pan.Shui. coal field, Guizhou Province, China, 35°~60° steeply inclined coal seams are widely distributed, and the coal resources present are of high quality and are mostly coking coal. However, because the roof overlying rock structure is affected by the geological conditions at a large dip angle, the combined cantilever beam structure of the overlying rock near the working face and the overlying rock masonry beam structure in front of the working face have different migration laws from when the condition of the near-level coal seam is generated. The pressure has emerged with new characteristics, posing a threat to coal mine production safety. Therefore, by establishing a mechanical model of roof overlying rock structure in accordance with the characteristics of coal seam inclination, mining height, and goaf overlap in the Liu.Pan.Shui mining area and using the analytical formula of material mechanics to calculate the behavior of rock pressure, guide the roof weakening means, construction technology, and parameters. It is used to quantitatively control the transportation load of the overlying rock on the roof of the large inclination coal seam and realize the safe and efficient mining of the precious coal resources of the Liu.Pan.Shui coal field.

1. Introduction

Steeply dipping coal seams refer to coal seams with buried inclination angles of 35°~55°, which are extremely difficult to mine. The composite roof is generally a roof composed of mudstone, shale, siltstone, and coal. Therefore, the high-incline composite roof working face is prone to roof fall and slicing. There are obvious differences in the characteristics of the pressure at both ends of the working face, and with the strike direction of the recovery, the appearance characteristics will also change. The roof is difficult to handle, and the support is difficult to handle. The quantitative control of resistance requires a high construction technology [1–5].

According to the national energy strategy plan, coal as a national strategic resource will still account for more than 50% of China's energy structure by 2025 [6]. It can be seen that coal resources will continue to escort the rapid development of China's national economy and the smooth operation of people's lives. Play the main energy status in the service process. Since October 2021, the coal supply situation has been severe, and power supply restrictions caused by insufficient coal resources have appeared in various parts of China, which have affected residents' lives and business operations to a certain extent. Therefore, under the background of the general trend of coal resources from east to west, Liu.Pan.Shui. is studied. The high-inclination coal resources that are ubiquitous in mining areas are highly and safely mined. The importance to the country and the people is self-evident.

For a long time, research studies on the plastic failure mechanism and deformation control of coal seam roadways, as well as the movement law of stope roof structure and the characteristics of rock pressure manifestation, have mainly focused on nearly horizontal coal seams, and the stope supports for steep and steep coal seams are reasonable. The study of the relationship between working parameters and roof structure activity law can effectively control the large-area asymmetric deformation of the overlying slab structure in the stope and the poor support effect caused by the advance and lag of the support of the working face. Combined with the general trend of intelligent matching of three machines in the working face, the quantitative relationship between the movement law of the support and the roof structure of the large-incline coal seam has become an important engineering problem that needs to be solved urgently to realize the safe, green, efficient, and intelligent mining of the large-incline coal seam.

Wu and Xie [3–5, 7] combined theoretical analysis, similar material simulation experiments, and multivariate numerical simulation technology to establish a mechanical model of a large-inclined coal seam stope. The study analyzed the characteristic law of the asymmetric distribution of the overburden stress field in the stope. It is believed that the failure of the rock strata will form trending and anti-trend stacking structures, and there are different failure structures in different areas along the tending direction of the rock strata.

Luo Shenghu et al. [8] systematically studied the failure and deformation characteristics of the floor of the high-incline coal seam by analyzing a large number of on-site monitoring results and theoretical analysis. The transfer action on the floor causes the mechanical properties of the rock formation to change, from the layered continuous medium state to a rock mass medium structure containing "structure + structural plane."

Hou et al. [9] studied the mechanical characterization and failure mechanism of shale rock specimens under different strain rates through laboratory experiments. Okubo et al. studied the failure characteristics of the two-stage rock specimens loaded in circular and triaxial directions with different loading rates. To a certain extent, it reveals the corresponding mechanism of the asymmetric plastic failure distribution of the roof overlying rock under the action of the deviator stress field of the high-dip coal seam when the roof lithology is shale (Mechanical Behavior of Shale at Different Strain Rates, RMRE, loading rate dependence of class II rock behavior in uniaxial, and triaxial compression tests, an application of a proposed new control method).

Guo et al. present key findings from a recent comprehensive study of longwall mining-induced strata movement, stress changes, fractures, and gas flow dynamics in a deep underground coal mine in Anhui, China. The study includes field monitoring of overburden displacement, stress, and water pressure changes at the longwall panel 1115 (1) of the Guqiao Mine. In addition, 3D modelling of strata behavior at the longwall panel using a 3D finite element code and goaf gas flow simulations with a CFD code is carried out. This research has resulted in many new insights into the complex dynamic interaction between mining-induced strata stress changes, fractures, and gas flow patterns.

2. Geological Survey of Large Dip Angle Working Face

Liu.Pan.Shui. coalfield is located in Liuzhi, Panxian, and Shuicheng, three special areas, as the center and adjacent to Weining, Nayong, Puding, Zhenning, Qinglong, Pu'an, and other counties; the total area is about 10,000 km^2. Coal resources are about 50 billion tons, reserves are 14 billion tons, and annual output is about 20 million tons. As the largest coalfield and coal industrial base in southwest China, it is generally faced with the problem of large dip angle coal seam mining [10–12]. The quantitative understanding of the roof migration law of large dip angle coal seam is of great significance for the parameter adjustment of working resistance of working face support, which is the escort for the green, safe, and efficient mining of high-quality coal seam with steep dip and large dip angle.

The case working face mainly mines No. 18 coal seam: the upper distance is about 38 m from the bottom of No. 15 coal seam, and the upper distance is about 9 m from the standard 7. There are 30 exposed layer sites, including 28 recoverable points and 2 unrecoverable points. The thickness of coal is 0.24~5.80 m, 2.06 m in average. Containing 0~6 layers of stone, generally 1~2 layers, the coal seam structure is relatively simple. The coal seams in this area belong to relatively stable medium thick coal seams. The roof is siltstone or mudstone, and the floor is mainly mudstone, followed by siltstone.

The rock in the range of caving and fracture zone above roof is mainly mudstone, siltstone, and siltstone interbed. The direct roof is interbedded with mudstone, siltstone, and fine sandstone. The compressive strength is generally 14.20~53.30 MPa, most of which are soft rock and some are hard rock. The tensile strength is 1.14~4.76 MPa, rock RQD value is 10~100%, generally 70%, and rock quality is poor to medium and belong to unstable to relatively stable roof. The floor is generally mudstone, aluminum mudstone, and siltstone. The thickness of mudstone is 0.28~1.32 m, and the general thickness is 0.45 m. The quality of the floor is poor, especially the aluminum mudstone is soft, and it becomes soft when encountering water.

3. Packing Structure Characteristics of Strata in Steeply Dipping Coal Seam Working Face

According to the different dip angle, rock lithology thickness, and mining thickness, the rock strata on the stope may appear as two kinds of accumulation methods, as shown in Figures 1(a) and 1(b). These two methods cause different shear dislocation sliding instability and rotary subsidence instability, which affect the distribution of stope abutment pressure and cause asymmetric distribution of both ends of the working face and the middle, as shown in Figure 1(c):

According to the moment equilibrium conditions around the rotation of different fulcrums and the

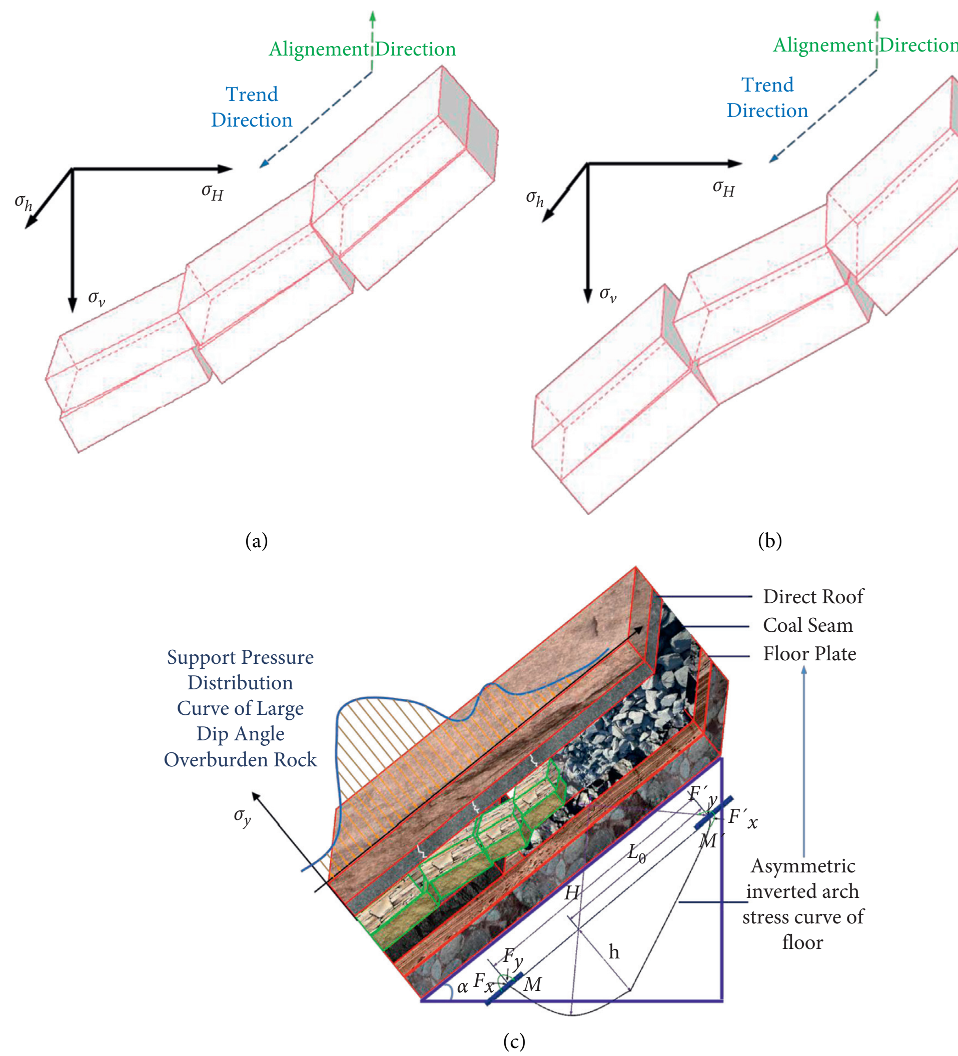


Figure 1: Stress characteristics of asymmetric inverted arch surrounding rock in stope. (a) Tendency accumulation structure formed by rock migration. (b) Anti-tendency accumulation structure formed by rock migration. (c) Asymmetric distribution mechanical model of abutment pressure in steeply dipping coal seam stope.

assumptions of material mechanics and structural mechanics, the stress analysis of the pile-up composite structure formed after the roof rock breaking is carried out. The roof rock structure of large dip coal seam stope is regarded as the movement of beam structure block under the stress condition of inclined fixed constraint boundary self-weight and uniform load on the boundary above the key layer, and it is assumed that the rock block meets the assumptions of material mechanics and elasticity. When the maximum subsidence deflection of the key rock block exceeds the position of the central line of the in-situ rock stratum, it is judged that the key rock block has structural movement instability at this time. By making the moment of rock block rotary sliding exceed the critical moment condition in the equilibrium formula, the structural sliding instability of the key rock block is judged. Through the force balance formula, the maximum unbalanced force at the hinge point between the fractured rock block and the in-situ rock layer exceeds the uniaxial compressive strength of the rock; it is considered that the material instability caused by the extrusion failure of the rock layer. When the maximum principal stress in any section of the rock beam exceeds the tensile strength limit of the rock material or the shear stress exceeds the product of the infinitesimal strain and the shear stiffness in the stress-checking formula, it is considered that the failure of the rock beam is caused by the tensile fracture of the rock stratum:

For the rotary instability of the key block B around the O point, after the force balance, the anti-dip stacking structure is formed with the structural blocks A and C and the surrounding rock blocks, which make the abutment pressure of the working face distribute in a basically symmetrical form along the inclined direction of the working face [13–15]. This is because the stable process of the blocks A, B, and C breaking, rotating, and sliding is overlapped to the gangue bearing structure to form a stable process. The acting load of the key block B on the structural block A is basically equal to its own weight after being subjected to the load transferred by the overlying rock mass and the horizontal extrusion of the stable block C. At the same time, the loading condition of structural block A directly determines the working resistance transmitted to the support. Therefore, when the key block B undergoes instability in the form of Figure 2(a), the resistance at both ends of the working face is somewhat increased but not obvious compared with that in the middle work, as shown in Figure 2(a). In order to quantitatively solve the action load of inclined stacking structure system on the support, it is necessary to analyze the force equilibrium condition of key block B [16–26].

For the moment equilibrium formula of key block B after rotary stability, $M_C = M_{CC} = 0$:

$$\begin{aligned} &Q(L + H\cot\theta) + G\cdot\cos\alpha\left(\frac{1}{2}L + \cot\theta\right) + T_A\cdot a_1 \\ &= T_C\cdot(H - a_2 - \Delta) + N\cdot\cos\alpha\left(\frac{1}{2}L + \cot\theta\right). \end{aligned} \tag{1}$$

When the key block B rotates around the O' point, the inclined accumulation structure is formed with the structural blocks A and C and surrounding rock blocks after the force balance, which makes the abutment pressure of the working face distribute asymmetrically at both ends along the inclined direction of the working face. The abutment pressure on the side of the inclined elevation is significantly less than that on the other side, as shown in Figure 3(b). This is because structural block A is not only subjected to the weight of the intrusive rock and the extrusion pressure from the key blocks B and C along the inclined direction but also subjected to the staggered shear force, which makes structural block A have the trend of rotary sliding to the working face, indirectly increasing the load on the working face support.

For the force-distance balance formula of key block B after turning around O' point, $M_C = M_{CC} = 0$:

$$\begin{aligned} &Q(L + H\cot\theta) + G\cdot\cos\alpha\left(\frac{1}{2}L + \cot\theta\right) \\ &+ T_A\cdot(H - a_1 - a_2 - \Delta) = T_C\cdot a_2, \end{aligned} \tag{2}$$

where $\Delta = \cos(\pi/2 - \alpha)\times(M + H) - K_pH$ is the rotational subsidence of key block B, m, M is the height of coal seam mining, m, α is coal seam dip angle, °, H is the thickness of key block B, m, k_p is the broken expansion coefficient of gangue in goaf, dimensionless, Q is the load stress of the simplified overlying strata on the key block B, N, L is the length of key rock block B, m, θ is the rotation angle of the key block B, °, T_A is the reaction force of stabilizing block A to key block B along the inclined direction, N, T_C is the extrusion force of lap stable structure block C to key block B along the inclined direction, N, a_1 torque around O point for force T_A, m, and a_2 torque around O point for force T_C, m.

The mechanical analysis of the composite cantilever structure block A shows that, apart from the weight of the upper composite rock block, the fault force provided by T_A has the greatest influence on the abutment pressure of the working face. Therefore, two analytical solutions of T_A are derived by formulas (1) and (2) for the key block migration forms of two inclined structures:

$$\begin{cases} T_1 = \dfrac{1}{a_1}\left\{\left[\left(2\gamma H^2\cdot\sqrt{\dfrac{R_t}{K(1-\sin\alpha)^2\sigma_c}} + h\gamma_1\right)\sin\alpha - f\cos\alpha\left(2\gamma H^2\cdot\sqrt{\dfrac{R_t}{K(1-\sin\alpha)^2\sigma_c}} + h\gamma_1\right)\right]\cdot\right. \\ \left(H - a_2 - \sin\alpha(M+H) + K_pH\right) + N\cos\alpha\left(H\sqrt{\dfrac{R_t}{K(1-\sin\alpha)^2\sigma_c}} + \cot\theta\right) \\ \left. -\gamma HL\cos\alpha\left(H\sqrt{\dfrac{R_t}{K(1-\sin\alpha)^2\sigma_c}} + \cot\theta\right)\right\} \\ T_2 = \dfrac{1}{H - a_1 - a_2 - \sin\alpha(M+H) + K_pH}\cdot a_2\sin\alpha\left(2\gamma H^2\sqrt{\dfrac{R_t}{K(1-\sin\alpha)^2\sigma_c}} + h\gamma_1\right) \\ -a_2 f\cos\alpha\left(2\gamma H^2\sqrt{\dfrac{R_t}{K(1-\sin\alpha)^2\sigma_c}} + h\gamma_1\right) - \dfrac{1}{2}K(1-\sin\alpha)^2\sigma_c\left[2H\sqrt{\dfrac{R_t}{K(1-\sin\alpha)^2\sigma_c}} + H\cot\theta - \gamma HL\cos\alpha\left(H\sqrt{\dfrac{R_t}{K(1-\sin\alpha)^2\sigma_c}} + \cot\theta\right)\right], \end{cases} \tag{3}$$

where K is the dimensionless coefficient determined according to the fixed or simply supported state of rock beam, generally 1/2~1/3, R_t is a key block on the tensile strength of the rock, MPa, γ_1 is the average volume force of rock, kN/m^3, and σ_c is uniaxial compressive strength, MPa. Because the expression of the formula is too long to facilitate the field application of measurement values into the calculation, then the following formula is given in the final simplified form:

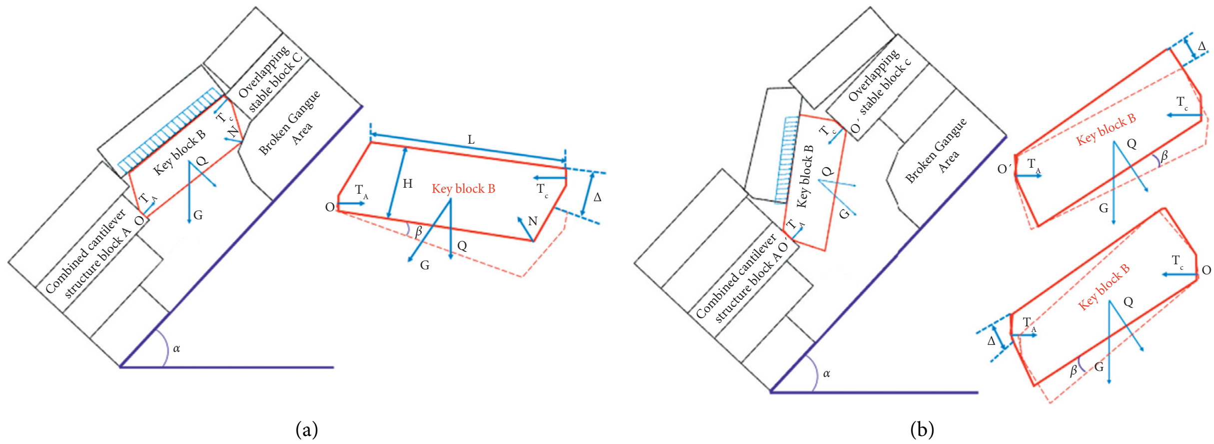


FIGURE 2: Force analysis of key block B of overlying strata in high-inclined coal seam stope. (a) The key block B is unstable around point O, forming an anti-trend to accumulate structure. (b) The key block B is unstable around O' point, forming a tendency to accumulate structure.

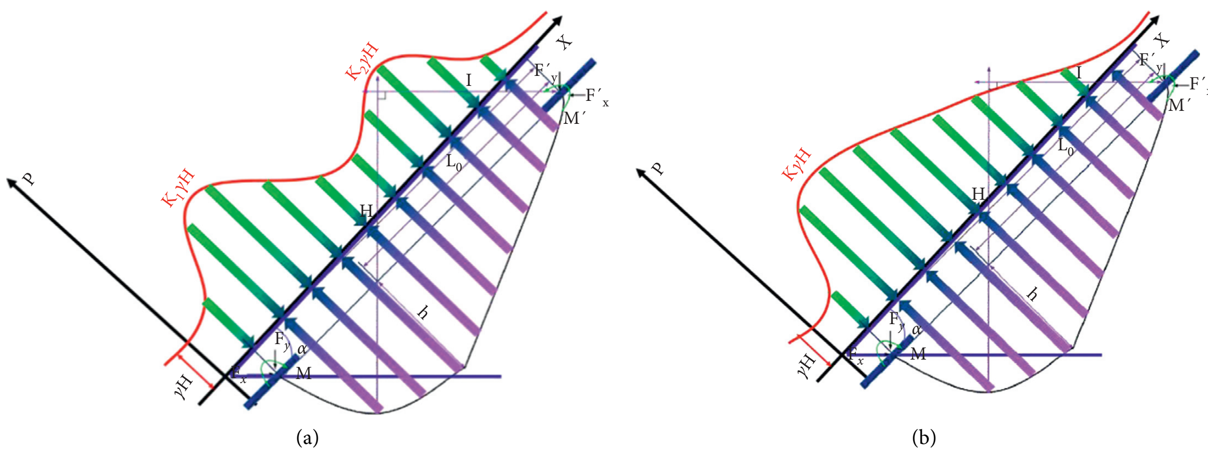


FIGURE 3: The distribution law of abutment pressure in the inclined direction of the working face under the condition of large inclination angle. (a) Support pressure distribution of working face under anti-inclined accumulation structure. (b) Support pressure distribution of working face under inclined accumulation structure.

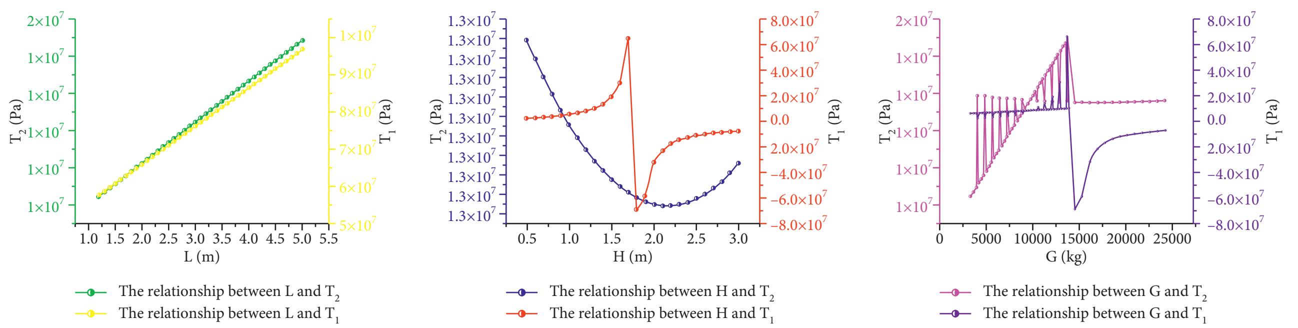
$$\begin{cases} T_1 = \dfrac{1}{a_1}\left[T_c\left(H - a_2 - \sin\alpha(H+M) + K_pH\right) + N\cos\alpha\left(\dfrac{L}{2} + \cot\theta\right) - \gamma HL\cos\alpha\left(\dfrac{L}{2} + \cot\theta\right)\right], \\ T_2 = \dfrac{T_c a_2 - \gamma h[L + H\cot\theta - \gamma HL\cos\alpha((L/2) + \cot\theta)]}{H - a_1 - a_2 - \sin\alpha(M+H) + K_pH}. \end{cases} \tag{4}$$

Taking 18# coal seam in a coal mine in Liu.Pan.Shui coalfield as an example, the actual measured value is taken into formula (4) to quantitatively solve the load transferred to the support of the working face by different inclined stacking modes through structural block A. 18# coal seam thickness is 0.25~5.60 m, and the average thickness is 2.30 m. The average dip angle of coal seam is 42°, which belongs to large dip angle coal seam, and the buried depth is about 140 m. The direct roof is mudstone, siltstone, and siltstone interbedded. The compressive strength is generally 14.20~53.30 MPa, most of them are soft rock and some are hard rock. The tensile strength is 1.14~4.76 MPa, and the formula parameters correspond to the unit and value in Table 1.

Use Mathcad 15.0 software to substitute the above parameters into formula (4) to sort out and calculate the changes in the physical and mechanical properties of the top slab of the key block and the working face of the high-dip coal seam. Increased to 5 m, thickness H increased from 0.5 m to 3 m; while recording the dynamic relationship between L and H, the weight of the key rock block (G), the asymmetric appearance of rock pressure on the working face has the influence law as shown in Figure 4.

Table 1: Liu.Pan.Shui. coal mine measured geological data parameter table.

Serial number	Parameter name	Symbol	Unit dimension	Value
1	Average key rock beam length	L	m	3.5
2	Coal seam dip	α	rad	42
3	Mining thickness	M	m	2.3
4	Average thickness of key rock beam	H	m	1.2
5	Volume stress	Γ	kN/m^3	23000
6	Buried depth	H	m	140
7	Coefficient of direct roof crushing expansion	K_p	Dimensionless	1.2
8	Angle of roof beam fracture	Θ	rad	15



(a) (b) (c)

Figure 4: Relationship between geometric physical characteristics of key blocks and strata behavior of working face in steeply dipping coal seam. (a) The relationship between key block length L and T_1 and T_2. (b) The relationship between the thickness H of the key block and T_1 and T_2. (c) The relationship between the weight G of key blocks and T_1 and T_2.

In Figure 4(a), when the breaking length of the key block B increases from 1 m to 5 m, the force T_1 of the structural block A with anticlinal accumulation on the support of the working face increases monotonously from 5.78 MPa to 9.704 MPa; the force T_2 of inclined accumulation structural block A on working face support also monotonically increased from 10.23 MPa to 14.45 MPa. When the thickness of key block B increases from 0.5 m to 3 m, T_1 increases from 2.5 MPa to 6.5 MPa, then decreases to upward force, and finally recovers to about 2.2 MPa. The decrease of T_2 from 13 MPa is not obvious. When the thickness H of the mechanical model of the roof slab rock layer increases from 1.5 m to 2.0 m, the curve section shows strange changes. This is because when the beam depth of the mechanical model of the rock beam increases and the span remains unchanged and when it exceeds a certain proportion, the properties of the mechanical model of the beam will be changed and defined and judged in the mechanics of materials. The weight of key block B has no obvious effect on T_1 and T_2. With the increase of G, T_2 is maintained at about 10 MPa. By analyzing the calculation results of the analytical formulas above, it is found that the load of the inclined structure on the support of the working face is generally greater than that of the reverse inclined accumulation structure when the inclined accumulation structure and the reverse inclined accumulation structure of the roof strata of the working face in the large-inclined coal seam are compared. When there is an angle in the inclined direction of the working face, the stress between the rock blocks hinged mutually along the horizontal direction is accumulated and transferred mutually, resulting in the asymmetric distribution characteristics of the stress, strain, and fracture form of the working face.

Due to FLAC (Fast Lagrangian Analysis Code), finite element simulation software can better analyze the interaction between the evolution law of stress field and displacement field of overburden and hydraulic load of the working face. Combined with the numerical simulation software Flac^{3D} 6.0, the calculation results of the above analytical formula were verified. The experimental scheme was set according to the geological and mining technical conditions of the working face of 18# coal seam in a coal mine. The experiment was divided into the most group of parameter values, the middle group of parameter values, and the parameter values according to the lithology of L and H and coating rock.

It is found from Figure 5 that the evolution law of stress and strain reflected by the three groups of experimental parameters is exactly the same as that reflected by the calculation results of the analytical formula, and the difference between the numerical values is not large. Therefore, it is considered that there is a close relationship between the migration law of roof overburden and the phenomenon of mine pressure in the steeply dipping coal seam and the key block structure of the roof. The control of the fracture length, thickness, and strength of the key block is also an important means to control the mine pressure of the working face of the steeply dipping coal seam.

It is feasible and effective control measures to reduce the size of L and H by means of roof cutting blasting, hydraulic

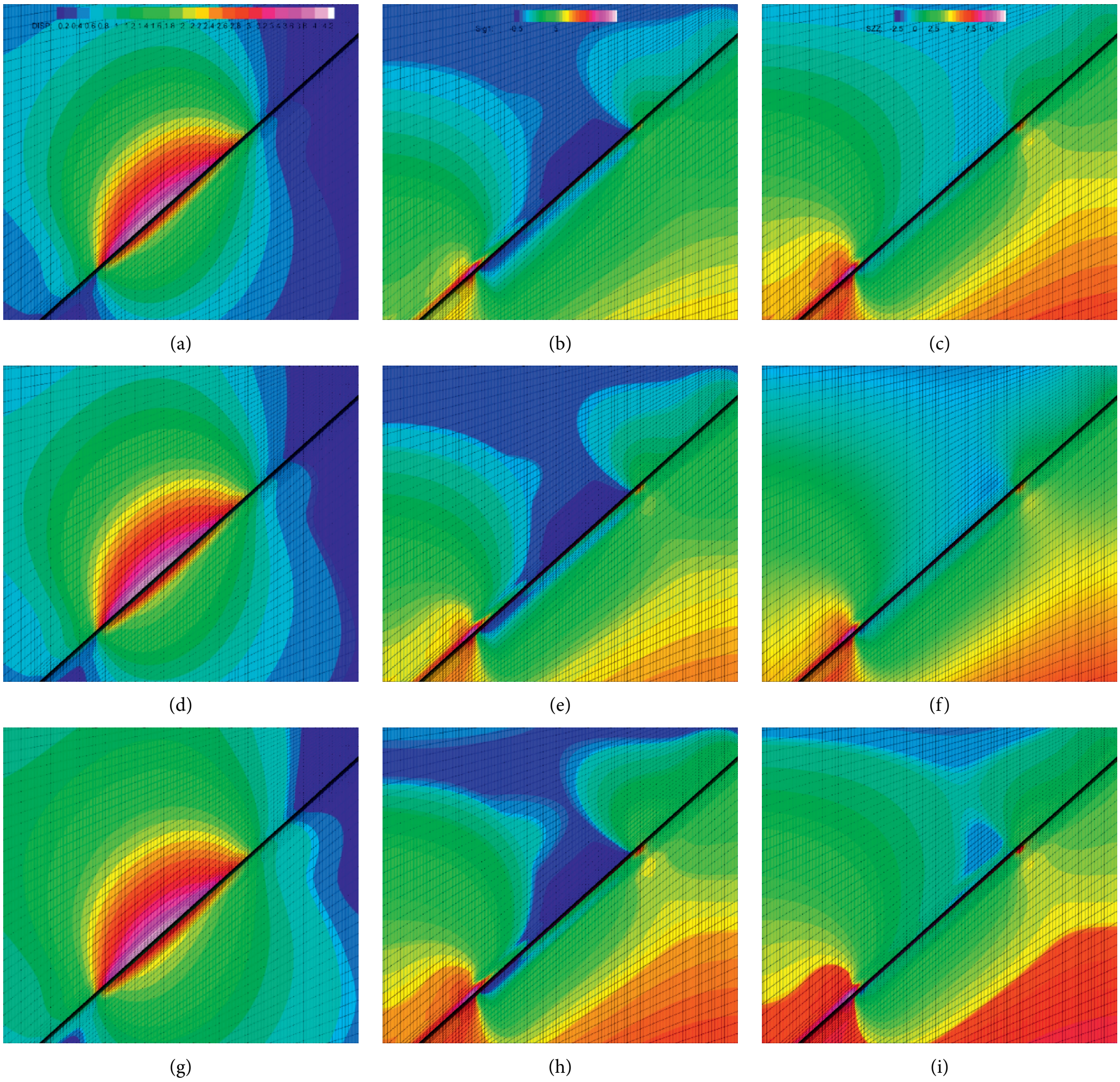


Figure 5: Numerical simulation test results of roof structure migration law in large-inclined coal seam. (a) Distribution characteristics of strain field of minimum parameters. (b) Distribution characteristics of maximum principal stress field of the most group parameter. (c) Distribution characteristics of the most small parameter lead direct stress field. (d) Strain field distribution characteristics of intermediate parameters. (e) Distribution characteristics of maximum principal stress field of intermediate group parameters. (f) Distribution characteristics of intermediate parameter straight stress field. (g) Strain field distribution characteristics of maximum group parameters. (h) Distribution characteristics of maximum principal stress field with maximum group parameters. (i) The distribution characteristics of the maximum group parameter lead stress field.

fracturing weakening, and appropriate adjustment of the advancing speed of the working face and to change the weight component of the composite structure block by adjusting the pseudoslope.

4. Conclusion

(1) The migration law of the stope roof in the working face of large dip angle coal seam is obviously different from that in the near-horizontal coal seam, which is also one of the reasons for the great difference in the strata behavior at both ends of the working face. In the process of migration, breaking, rotation, sliding and sinking of covered rock, two different combinations of key blocks, i.e., inclined accumulation and anti-inclined accumulation, are formed. In order to avoid excessive abutment pressure and severe and uncontrollable strata behavior, the formation of inclined structure should be avoided.

(2) Under the condition of large dip angle, the length, thickness, and lithology of key rock mass become the most important factors affecting the strata behavior

of working face. Therefore, the pretreatment of roof strata of the working face becomes the necessary means to prevent the strong strata behavior of the working face and reduce the potential safety hazard of the working face in large dip angle coal seam.

(3) In order to reduce the degree of mine pressure behavior and the inconsistency of the control of the two ends of the support equipment in the process of advancing the large dip angle working face, the hydraulic fracturing in the advanced roadway, deep space blasting, and water injection weakening are used to quantitatively control the load concentration of the roof movement of the large dip angle working face in the Liu.Pan.Shui coalfield of Guizhou. To illustrate the reliability and universal application of hydraulic fracturing technology to roof treatment [27–30].

Data Availability

The experimental and analytical calculation results data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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