

Article

Influence of Different Mining Parameters on Collaborative Bearing Characteristics Between Hydraulic Supports and Surrounding Rock Coupling System

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Abstract

Hydraulic support (Hs) is an important support equipment in coal mining. With the continuous increase in coal mining intensity, stricter technical specifications have been put forward for the effectiveness of Hs. Hs is always in a dynamic coupling state with the surrounding rock. Investigating its dynamic adaptation characteristics in relation to surrounding rock is of great significance for improving its performance. In this work, a numerical analysis model of the ‘support–surrounding rock’ coupling system was established by taking the Hs (type ZZ 17000/33/72D) in the Kouzidong coal mine as an example and using explicit dynamic analysis software Ls-dyna R12. The dynamic response and pressure distribution characteristics of the hydraulic ‘support–surrounding rock’ coupling system under different mining heights and load conditions were investigated. The key vulnerable connection components of the Hs and their critical connection unit instability conditions were identified. These findings provide a theoretical basis for the structural optimization of four-column Hs, which will be beneficial in promoting the improvement of its load-bearing stability.

Keywords: large mining height; four-column hydraulic support; perimeter rock coupling; connection unit



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1. Introduction

China’s coal resources occupy the main position in the overall energy structure, and the mining industry is the basic industry of the national economy. According to the ‘Statistical Bulletin on National Economic and Social Development in 2023’ released by the National Bureau of Statistics, the total annual amount of coal reached 4.71 billion tons in 2023, representing a year-on-year increase of 2.9% [1]. Furthermore, the total amount of coal mining is increasing every year. Numerous ultra-thick coal seams are concealed in China’s central and western regions (more than 40%), and further mining of these seams will be the general trend. In recent years, with the continuous upgrading of mining equipment and methods, the full-thickness mining method of large height has gradually become one of the important ways of thick-coal-seam mining [2]. As the mining height of the

working face increases, the strength and frequency of roof compression also gradually increase [3,4]. Therefore, supporting the roof of the fully mechanized coal face effectively while ensuring safe production is an important issue that requires continuous attention. As the key support equipment for coal mining, Hs is always in a dynamic coupling state with surrounding rock in the working process. Hence, investigating the cooperative load-bearing characteristics of Hss and surrounding rock is significant for ensuring safe and efficient mining in large-mining-height working faces.

Four-column Hs is a common frame type in mines with severe impact pressure due to its strong bearing capacity and high stability [5]. Due to the importance of the synergistic effect between Hss and surrounding rock for the safe support of working faces, many researchers have conducted extensive research in related fields. In the field of static load mechanical characteristics analysis of Hs, Trueman et al. [6] proposed that the characteristic load cycle of Hs can mainly describe the interaction between long-wall support and the roof. Xu et al. [7] developed a mechanical model for stiffness coupling between support and surrounding rock to examine the coupling system of support and surrounding rock through the lens of stiffness coupling. Furthermore, they validated this model through practical application examples. Han et al. [8] examined the impact of support stiffness on the solidity of the coal wall in the context of large mining heights. The authors found that the sensitivity of coal wall stability to support stiffness decreased with an increase in support stiffness. Zhang et al. [9] studied the static characteristics of hydraulic supports by establishing a scaled down numerical model of the support and found that the displacement and attitude changes in the support are more sensitive to the offset loading condition of the top beam. Meng et al. [10] conducted a static analysis of Hs under different load conditions by establishing LCCA mathematical models to study the failure mechanism of ultra-high mining Hs. They found that the main factor causing support failure was the deviation in the roof load from the equilibrium zone of the top beam.

In the field of dynamic-load mechanical characteristics analysis of Hs, Zeng [11,12] investigated the effects of diverse loading conditions on the transmission in Hss. Moreover, the authors employed numerical simulation analysis to ascertain the distribution patterns of their load characteristics. Yang et al. [13] conducted similar simulation experiments and field tests to study the stability of the roof structure and the mechanism of dynamic load generation in large mining heights. They found that the basic constant pressure would form a three-hinge arch structure, which could easily increase the impact of dynamic loads on the working face. Xie et al. [14] analyzed the adaptability of the four-column Hs at each position of the top beam and found that the efficient support area of the top beam can be expanded reasonably by increasing the column spacing. Prusek et al. [15] introduced the concept of a ground response curve (GRC) through numerical simulation and analyzed the interaction between the support system and the surrounding rock during natural roof fall in the gob area while identifying the GRC for two coal mining faces. Wu et al. [16] proposed a new quadrilateral hydraulic support structure. By establishing a hydraulic support dynamic model combined with the new structure, the dynamic response characteristics of the hydraulic support structure were analyzed, and it was found that the new structure significantly improved the safety of the hydraulic support. Szuergacz et al. [17] simulated impact loads through the free fall of objects, studied the response characteristics of columns under impact loads, and established the working parameters of columns.

In the related field of coupled analysis between the support–surrounding rock load characteristics [18–20], Wang proposed the coupling theory of support and surrounding rock and established the corresponding coupling model to analyze the stability of large-mining-height working faces. The crucial factor for the stability of the coupling system between support and surrounding rock is the stability of the support and its adaptability

to the instability of rock strata. Xu et al. [21] analyzed mine pressure patterns and roof subsidence curves to address the difficulty in controlling the surrounding rock in fully mechanized mining faces with large heights. Their findings revealed that mining faces with large mining heights exhibit distinct regional pressure and that mine pressure significantly influences roof subsidence. Zhang et al. [22] investigated the impact of the support's working state on the surrounding rock and analyzed the pressure regulation test curve of the support and surrounding rock associated with the support. Xu et al. [23] considered the support and its nearby surrounding rock as a small-scale structure and the fracture instability of the overlying rock as a large-scale structure to explore the interaction mechanism between the support and the surrounding rock. Then, the authors analyzed the impact of the coupling effect between these 'large and small structures' within the system on the stability of the working face. Gao et al. [24] introduced a numerical simulation approach for modeling the progressive collapse of rock strata in coal mining faces. This approach agrees with field observations from the Ruhr coalfield. Gao et al.'s findings indicate that compression–shear failure is the primary failure mechanism within the karst cave strata above the gob area. The proposed numerical method can serve as a valuable approach for guiding the design of surrounding rock support systems.

Witek et al. [25] conducted finite element analysis and experiments to investigate the pressure distribution of Hss under various operating conditions. Their findings indicate that the pressure distribution of the support is notably affected by the coupling form of the surrounding rock. The authors also concluded that improved coupling conditions can reduce the support's pressure values. Song et al. [26] explored the convergence and constraint mechanism of support and surrounding rock. The authors found that increasing the stiffness of support reduces the pressure of the coal wall and controls the rotation of the main roof. Feng [27] analyzed the coupling relationship between the support system and surrounding rock to address the issue of coal fragmentation in the working face and then conducted industrial testing. The problem of coal fragmentation in the working face was resolved by implementing different control modes during the weighting and mining periods.

Comprehensive analysis of existing research on support–surrounding rock interactions indicates that current investigations predominantly simplify structural components as rigid bodies, thereby neglecting the critical influence of deformational compliance on dynamic coupling effects between supports and strata. Crucially, the assumption of rigid columns obscures the mechanical response mechanisms associated with height variation during column displacement adjustment under load, which governs the coordinated load-bearing behavior of the coupled system. To address these limitations, this work employed the ZZ17000/33/72D Hs (the hydraulic support type used in the Kouzidong coal mine) as the research prototype and established a comprehensive deformable body model encompassing roof, surrounding rock, Hs, and floor. The hydraulic columns were substituted with equivalent springs to simulate their compliant deformation characteristics. Through parametric variations in mining height and roof loading across multiple operational scenarios, the model systematically characterized the dynamic load-bearing behavior of the coupled system while identifying load distribution features at near-instability states under various mining conditions.

2. Establishment of the Model for 'Support–Surrounding Rock' Coupling System

2.1. Establishment of Model for Hs

The ZZ17000/33/72D-type Hs of the 140,502 working faces in the Kouzidong coal mine was selected as an example, and its dynamic analysis model was established. The

design parameters of the selected Hs are shown in Table 1 [28]. The number 17,000 represents the working resistance of the support as 17,000 kN. Numbers 33 and 72 represent the minimum and maximum operating heights of the support as 3.3 m and 7.2 m, respectively. A three-dimensional model of the Hs is shown in Figure 1.

Table 1. Hs design parameters.

Mining Height/mm	3300–7200	Working Resistance/kN	17,000
Center distance/mm	1750	Support pressure/MPa	1.73–1.78
Width/mm	1680–1880	Pumping station pressure/MPa	37.50
Setting load/kN	12,977	Weight/kg	60,000

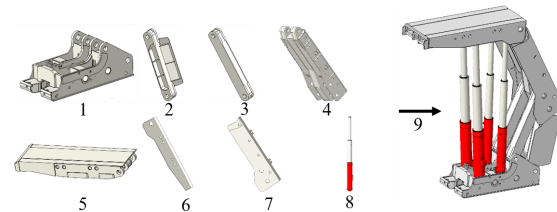


Figure 1. Three-dimensional models of Hs. 1—base; 2—back link; 3—front link; 4—shield beam; 5—top beam; 6—top beam side guard plate; 7—shield beam side guard plate; 8—column; 9—Hs assembly.

2.2. Establishment of the Dynamic Model for the ‘Support–Surrounding Rock’ Coupling System

The dynamic model for ‘support–surrounding rock’ coupling system is established to explore the interaction between Hs and surrounding rock. The material parameters of the roof and the floor are shown in Table 2 [29]. Based on the parameters in Table 2, the dynamic model for the ‘support–surrounding rock’ coupling system is given in Figure 2. The main model of Hs was established using the MAT_24 material unit. The unit is derived from the piecewise linear plasticity model in LS-DYNA. The model has a strike length of 15 m and a roof thickness of 24.6 m.

Table 2. Material properties of the ‘support–surrounding rock’ coupling system.

Name	Material	Density kg/m ³	Poisson Ratio	Elastic Modulus GPa
Hydraulic support structure	Q890	7860	0.30	211
Roof	Sandy mudstone	2500	0.30	3.60
Coal seam	No. 3 coal seam	1800	0.30	0.55
Floor	Fine sandstone	2700	0.25	4.80

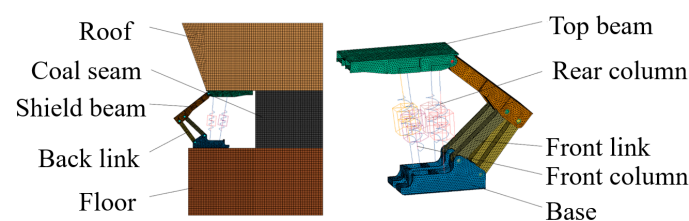


Figure 2. Coupling analysis model of four-column hydraulic support–surrounding rock system.

The burial depth of the working face in the Kouzidong coal mine is 1000 m, and the rock density measured by uniaxial compression is 2500 kg/m³, with gravity acceleration of 9.8 m/s². Through substitution in a formula [30] ($\sigma_v = \rho gh$, where σ_v represents the roof pressure, Pa; ρ represents the density of rock, kg/m³; g represents the gravitational acceleration, m/s²; and h represents burial depth, m), the pressure is calculated to be

24.5 MPa. In considering the roof structure and pressure conditions on site, the applied pressure is rounded to 15 MPa (reaching equilibrium and stability within 0.7 s).

An equivalent column spring damping system was used between the top beam and the base when establishing the ‘support–surrounding rock’ coupling system. This system was then imported into Hypermesh 2020 software for simulation. Due to the large size of the Hs component, if the mesh size is too small, it will result in a large number of grids. Consequently, the simulation solution time will be greatly increased, and the accuracy of the solution will not be improved. Therefore, the mesh size coefficient of the support was set to 0.04 in this work. The connection of each component was set as a rigid connection node, and a rigid connection unit was used to simulate the connection mode between the support components [31].

3. The Influence of Mining Height on the ‘Support–Surrounding Rock’ Coupling System

The coal seam thickness of the coal mine varies from 4 m to 7 m. As the working face advances, the working height of Hs varies with the coal seam. Therefore, the dynamic characteristics of the ‘support–surrounding rock’ coupling system under four typical mining heights (4 m, 5 m, 6 m, and 7 m) was analyzed.

3.1. Analysis of Dynamic Characteristics of Support Column Under Different Mining Heights

The dynamic response of the Hs column system under different mining heights is shown in Figure 3. The load curves of a column under different mining heights all exhibit a characteristic pattern: a rapid initial increase, followed by a slower rise, and ultimately stability at a constant value. Before 0.1 s, the external load was lower than the initial support. The load growth rate is fast, but the displacement of the column is small. After 0.1 s, the external load is greater than the initial support. In addition, the rapid contraction of the column leads to a decrease in column load due to compression. Then, the system force reaches equilibrium, and the column load and displacement tend to a stable value. For the mining height of 4–7 m, the displacement of the rear column is greater than that of the front column, causing an obvious ‘raised’ phenomenon to appear at the support. For mining heights of 4 m, 5 m, 6 m, and 7 m, the displacements of the Hs’s front column were measured as 15 mm, 20 mm, 24 mm, and 35 mm, respectively, while the displacements of the rear column were 19 mm, 24 mm, 29 mm, and 40 mm. Moreover, the maximum difference between the displacement of the rear column and that of the front column of the support was 15 mm at a height of 7 m.

3.2. Analysis of Connection Units’ Load Under Different Mining Heights

Figure 4 shows the dynamic response of the connection units under different mining heights. From Figure 4a–c, it is observed that the load of the connection unit first increases and then decreases from 0 to 0.2 s and then increases and stabilizes from 0.2 to 1 s. The load on the connection unit of the support increases with the application of external load between 0 and 0.1 s. When the external loading time is 0.1–0.2 s, the top beam undergoes horizontal displacement switching with the increase in external load and the rotation of the top beam. The displacement switching prompts the support connection unit to release the horizontal load during this time period. After 0.2 s, the external load of the system reaches a steady state, and the force response of the connection unit gradually increases and tends to balance under the action of the external load.

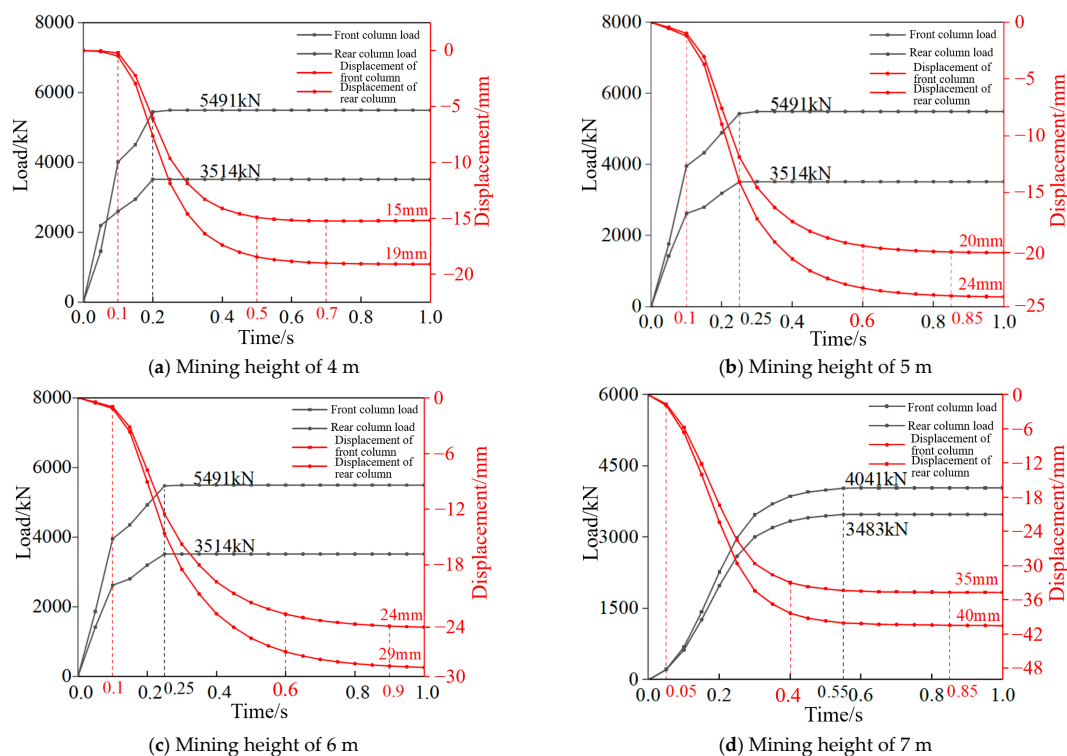


Figure 3. Dynamic response of column system under different mining heights.

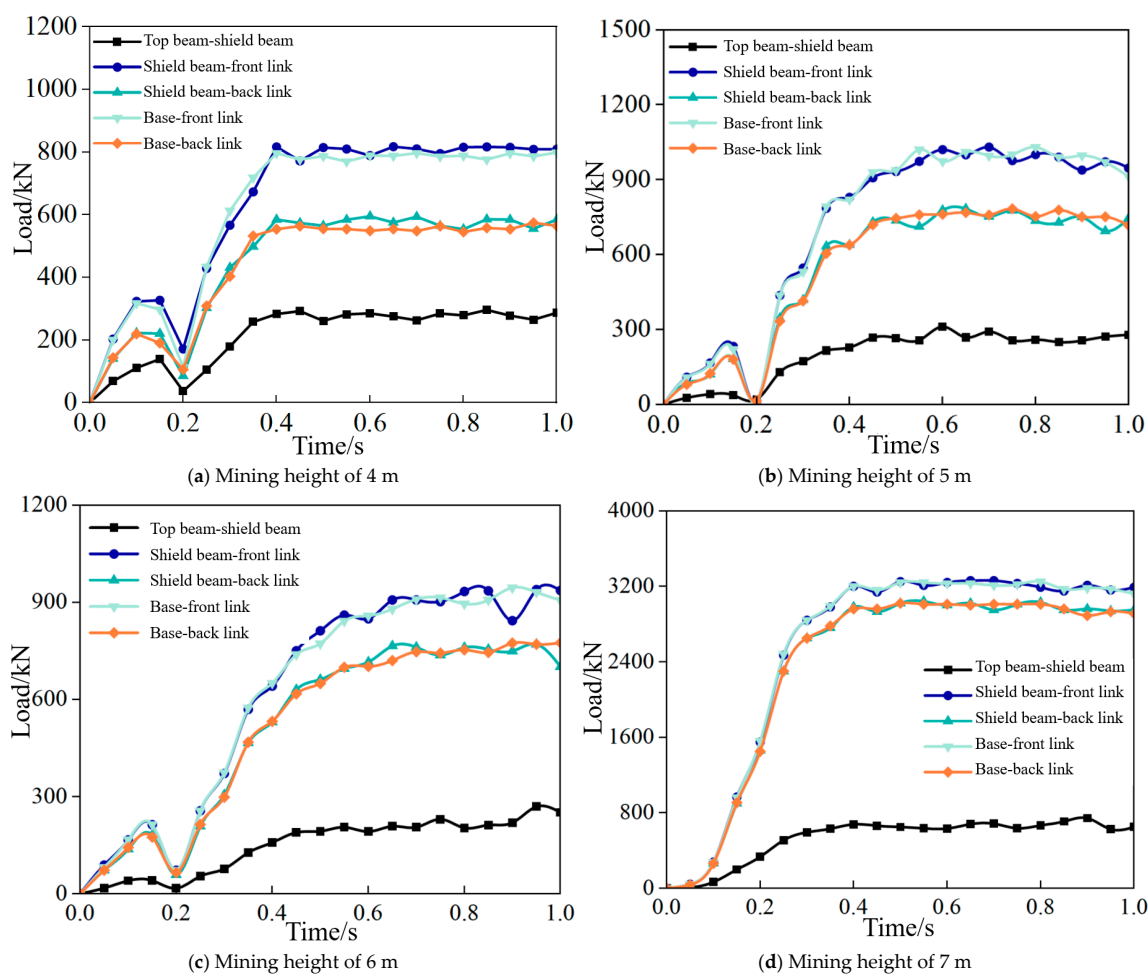


Figure 4. Dynamic response of connection units under different mining heights.

In contrast, the load variation trend at the 7 m mining height differs significantly from other heights (Figure 4d). At this height, the connection unit load increases and then stabilizes directly. This distinct behavior occurs because the 7 m height approaches the support's maximum capacity of 7.2 m. Under these conditions, both the hydraulic columns and connection units simultaneously bear substantial loads, different from the case at other mining heights. Thus, the connection unit load trend at 7 m demonstrates an initial rise followed directly by stabilization.

Across the 4–7 m mining height range, the minimum connection unit load consistently occurs at the roof beam–shield beam connection unit and remains substantially lower than loads at other connection units. In contrast, the maximum connection unit load occurs at the shield beam–front link connection unit, reaching 3240 kN at the 7 m mining height.

3.3. Analysis of Top Beam Displacement Under Different Mining Heights

The longitudinal node displacement of the top beam generally shows a linear distribution, as illustrated in Figure 5. From the front to back end, as the mining height increases, the downward displacement of the top beam gradually increases, and the 'raised' trend of the support gradually increases. The displacement at the 4 m mining height grows from 11.1 mm to 21.7 mm, while the displacement at a mining height of 5 m expands from 13.7 mm to 26.4 mm. At a mining height of 6 m, the displacement increases from 16.4 mm to 31.3 mm. In contrast, at a mining height of 7 m, support displacement increases from 22.5 mm to 43.6 mm. The displacement difference is 21.1 mm, much higher than the displacement difference of 10.6 mm at the 4 m mining height.

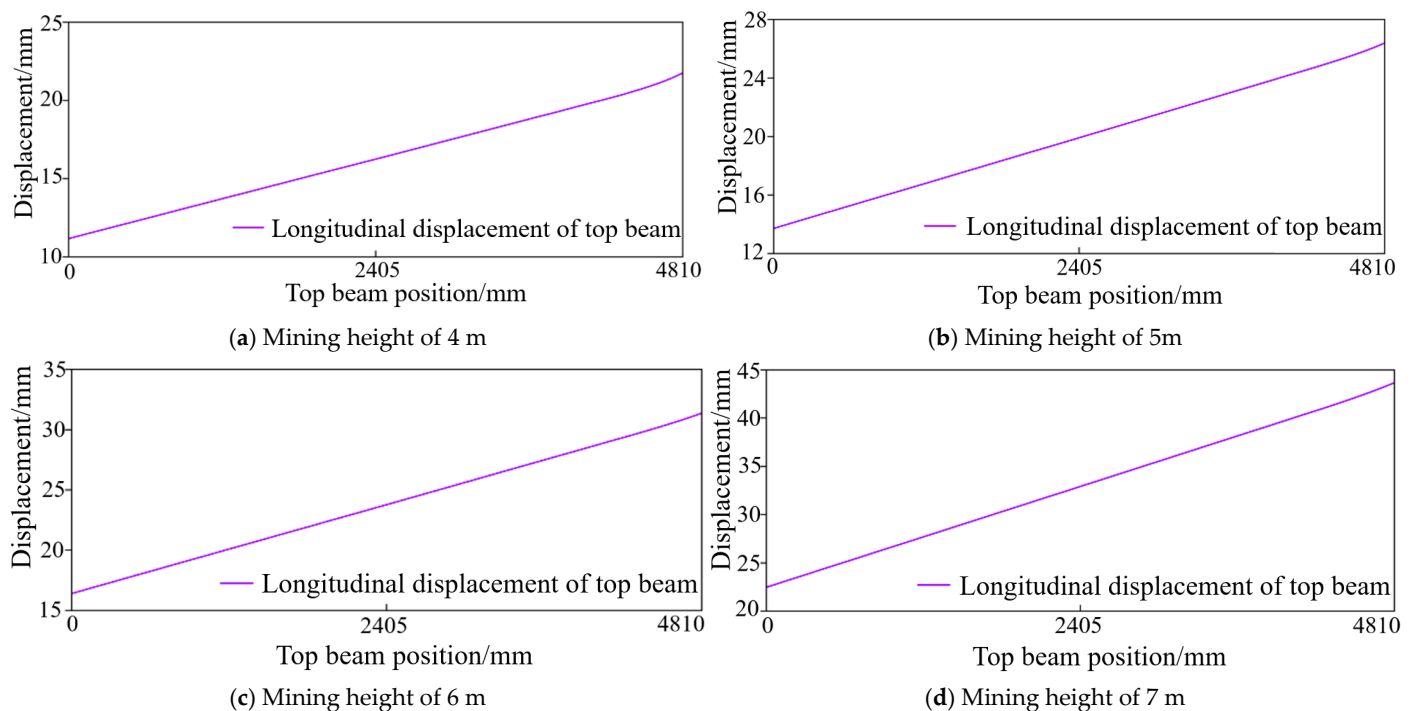


Figure 5. Displacement of roof beams under different mining heights.

3.4. Analysis of Surrounding Rock Pressure Under Different Mining Heights

The pressure distribution in the surrounding rock at various mining heights is shown in Figure 6. Initially, the Hs is in a rigid support state. Hence, pressure is concentrated above the roof and beneath the interface between the base and the floor, reaching approximately 4 MPa. The maximum pressure on the support occurs at the column socket positions of the front and rear columns of the base when mining at a height of 4 m. Specifically, the peak

pressure at the column socket of the front column reaches 8 MPa. At 0.2 s, the floor of the front column area reaches a peak of 20 MPa. When the mining height is 5 m, the pressure intensity range above the top beam and below the base is expanded at 0.2 s. At the same time, the surrounding rock of the support stabilizes. Moreover, the H_s continuously reduces the column pressure and gradually forms a mechanical balance with the surrounding rock. At this time, a pressure concentration zone appears at the inner vertex junction between the roof, coal seam, and floor. Pressure distribution exists in the coal wall near the fully mechanized coal face. The two form a ‘dumbbell’ pressure zone, and the peak pressure is approximately 9 MPa.

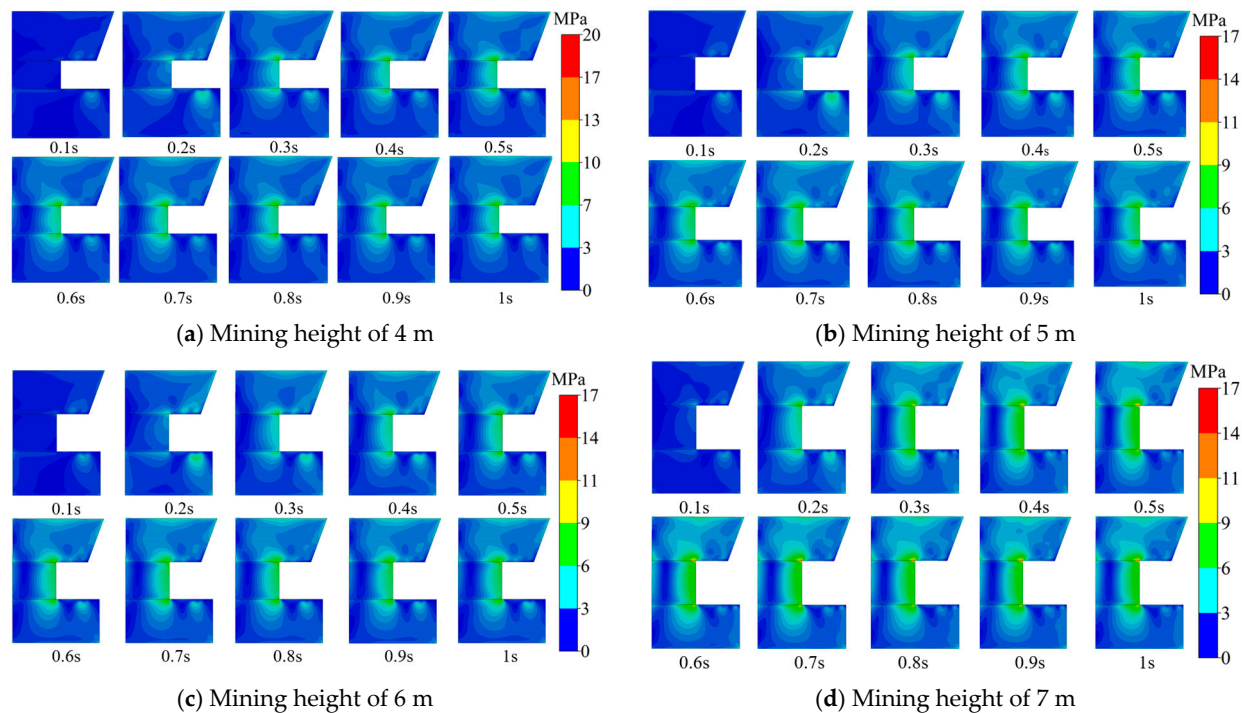


Figure 6. Pressure distribution in the surrounding rock under different mining heights.

The pressure distribution map at a mining height of 6 m is shown in Figure 6c. It can be observed that the load pressure above the top beam and below the base intensifies at 0.2 s. Simultaneously, the pressure concentration zone beneath the base diminishes and shifts toward the lower right. With time, the pressure concentration zone at the juncture of the inner vertex among the roof, coal seam, and floor progressively expands, with the peak pressure reaching approximately 10 MPa. The load affects the uniform loading area on the upper part of the roof. Moreover, the edge follows a ‘U’-type pressure distribution, forming a pressure band area between the roof pressure peak areas. The pressure exerted in this region is approximately 5 MPa. The pressure distribution map of surrounding rock for a 7 m mining height is shown in Figure 6d. At 0.2 s, there is a ‘U’-type pressure concentration area above the roof, a pressure concentration distribution above the contact position between the roof and the end of the roof beam, and a ‘dumbbell’-type pressure distribution area at the junction of the coal seam, the roof, and the floor. The maximum value is 7 MPa. With time, the ‘U’-type pressure zone of the roof diffuses and forms a pressure zone at the junction with the coal seam. This zone is located at the connection unit between the coal seam and the floor, spreading toward the bottom, forming a semi-circular pressure zone with a maximum of approximately 9 MPa. The longitudinal extension pressure zone at the coal seam gradually widens and becomes flat with the pressure zone. The peak pressure

occurs at the interface between the roof and protruding contours of the coal seam, with a magnitude measured at 15 MPa.

3.5. Analysis of Each Support Component Pressure Under Different Mining Heights

The pressure distribution of the main bearing components of the support when the system is balanced at 4 m mining height is shown in Figure 7a. The pressure at the top beam column socket is 150 MPa, and the pressure of the shield beam is non-uniform. The pressure in the middle area near the front link side on the back increases and diffuses to both ends of the shield beam. The pressure at the shield beam is 12 MPa. The base is a complex box structure. When the balance is reached, the pressure at the base is roughly 66 MPa.

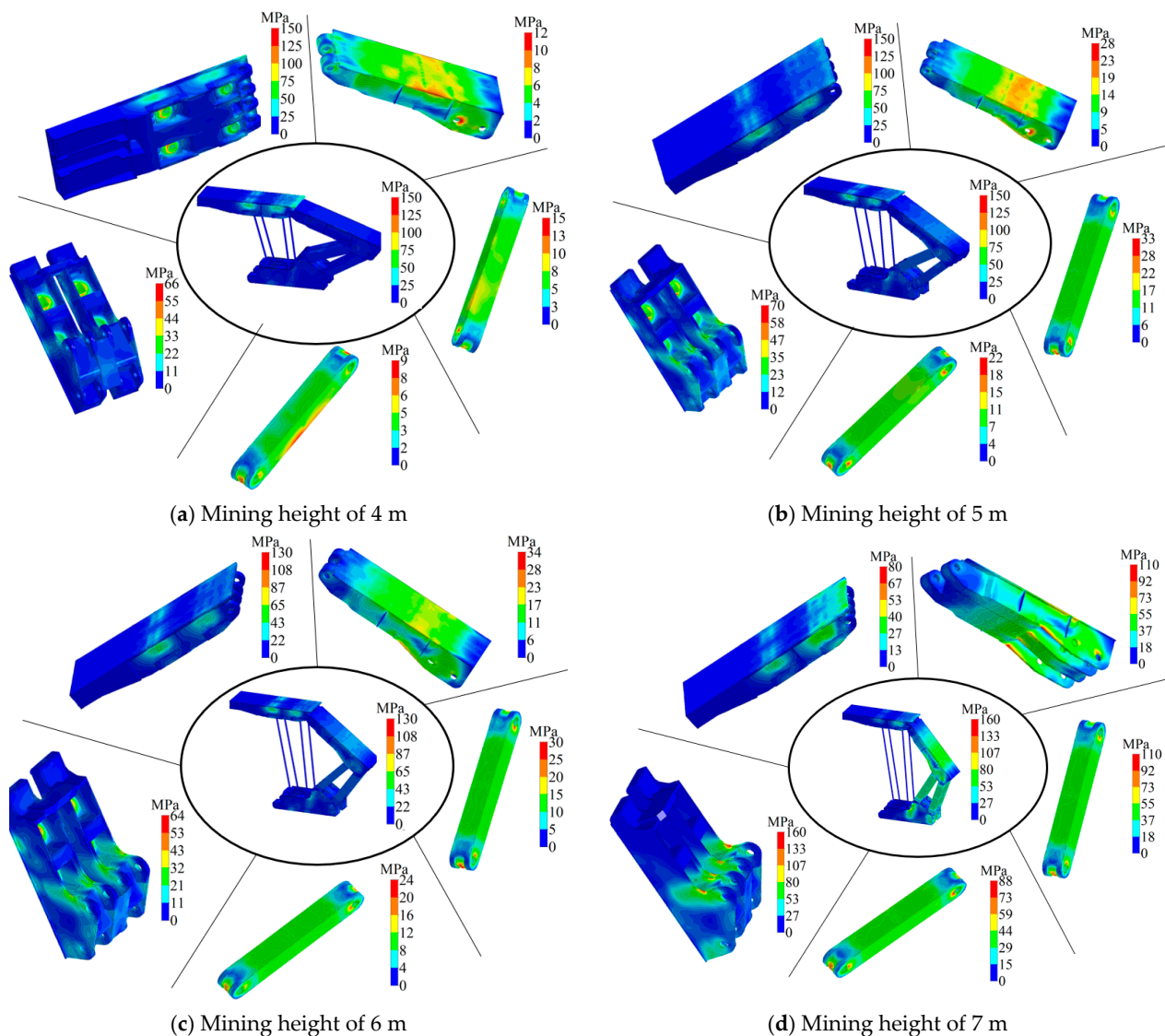


Figure 7. Pressure distribution of support components under different mining heights.

The pressure distribution of the main bearing components of the support when the system reaches equilibrium at a 5 m mining height is shown in Figure 7b. A pressure distribution of 150 MPa is observed in both the front column socket and the top beam back area. The pressure on the shield beam is 28 MPa, while the pressure at the back surface side of front link is concentrated with a maximum value of 20 MPa. The pressure at the rear link is 22 MPa, and the pressure in the middle of the rear link is 11 MPa. The focal region

of the base is transferred from the central area of the column socket at the start of the arc transition position at the side guard plate; here, the pressure is 70 MPa.

The pressure distribution of the main bearing components of the support when the system reaches equilibrium at a 6 m mining height is shown in Figure 7c. The concentration zone appears at the top beam back, and the maximum pressure reaches 130 MPa. The pressure concentration area is the middle box of the shield beam, and the peak pressure of 34 MPa is located at the connection between the side guard plate and the inner box. The pressure of the front link is symmetrically distributed along the middle rib plate. The pressure at both ends of the link is the lowest. The pressure at the outer side of the front link is slightly lower than that at the inner side, reaching 30 MPa. The pressure in the rear and front links is evenly distributed, measuring 24 MPa. When balanced, the pressure intensity of the base is 64 MPa, and the pressure at the back end of the base and the arc transition position reaches 54 MPa.

The pressure distribution of the main bearing components of the support when the system reaches equilibrium at 7 m mining height is shown in Figure 7d. In the initial state of equilibrium, the peak pressure in the focal region of the top beam moves back to the top beam back and reaches 80 MPa. The pressure concentration area of the shield beam is the middlebox and the connection between the side guard plate and the inner box. Contrary to the first three working conditions, the peak pressure on the shield beam is concentrated on the connection unit of the shield beam–rear link and reaches 110 MPa. The pressure intensity of the front and rear connection units is relatively high and symmetrically distributed along the middle rib plate. The pressure at both ends of the link is the lowest. The peak pressure at the front link reaches 110 MPa. The pressure distribution of the rear link is the same as that of the front link, reaching 88 MPa. The pressure of the base is mainly concentrated at the arc transition position of the guard plate and below the connection unit of the front and rear links. The maximum numerical value is located at the arc, reaching 160 MPa.

4. Influence of Roof Pressure on ‘Support–Surrounding Rock’ Coupling System

A mining height of less than 7 m was used to investigate the influence of roof pressure variations on the ‘support–surrounding rock’ coupling system. Roof pressure of 2–4 MPa was applied above the roof, and the impact of roof pressure on the pressure distribution pattern within the ‘support–surrounding rock’ coupling system was analyzed. According to Figure 8, the pressure distribution of the link was concentrated. The pressure at the top beam was concentrated in the rib support structure of the front and rear columns. In contrast, the pressure in the shield beam was predominantly concentrated in the area where it is a connection unit to the link. The peak pressure of the support was located in the arc transition structure of the side guard plate of the base and diverged in a weakened form around it. The pressure distribution of Hss was compared under different roof pressures. It can be observed that variations in roof pressure have no significant impact on the pressure distribution of the supports. As the roof pressure increases, the maximum pressure of the support steadily increases from 180 MPa to 350 MPa.

The floor pressure distribution under various roof pressures is depicted in Figure 9, which shows that the roof pressure has no significant impact on the pressure distribution pattern of the floor. When the impact load reaches the peak value, the contact pressure between the support and the floor forms a ‘Tian’ shape distribution in the column socket area. The peak pressure is located in the center of the column socket. The pressure intensity is lower at the contact point where the base back meets the floor. In contrast, the pressure at the juncture of the floor and the coal wall is higher and extends longitudinally along the

coal seam. The peak pressure of the floor is reduced by about one-third once the pressure balance of the surrounding rock system is reached. Consequently, the pressure intensity at the end of the floor is significantly enhanced. Lastly, the pressure intensity in the column socket area and the pressure concentration range at the rear column socket are reduced.

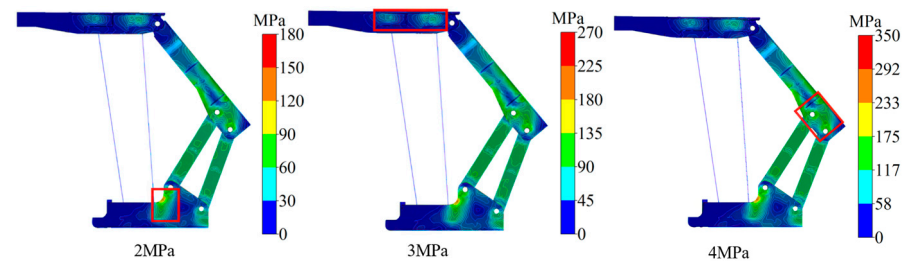


Figure 8. Pressure distribution of Hs under different roof pressures.

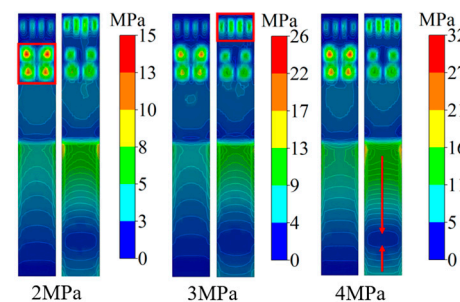


Figure 9. Pressure distribution of the floor under different roof pressures.

The pressure distribution map of surrounding rock under different roof pressures is shown in Figure 10. The pressure distribution trend of surrounding rock slightly affects the roof pressure. The peak pressure of the surrounding rock is situated at the junction of the roof and coal wall. The pressure increases from 15 MPa to 32 MPa; the pressure growth rate is fast at first and then slows down. Localized pressure concentrations occur within the surrounding rock immediately above the top beam and beneath the base. Here, the pressure intensity is approximately one-third of the peak pressure. The pressure contour of the coal wall is densely distributed and extends to the depth of the coal seam. A semi-circular concentrated area is formed at the junction of the coal wall, roof, and floor. An inverted triangle pressure distribution area is formed above the roof due to the influence of uniform load. The maximum pressure is approximately half of the peak pressure.

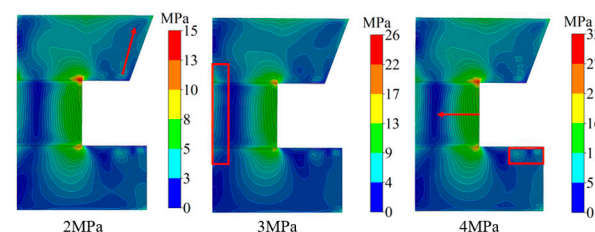


Figure 10. Pressure distribution of surrounding rock under different roof pressures.

The load changes at the connection unit of the ‘support–surrounding rock’ coupling system with respect to roof pressure are presented in Figure 11. As roof pressure increases, the load on each connection unit of the Hs generally rises, initially at a fast rate and then slowing down. Notably, the connection unit load of the top beam–shield beam experiences the smallest increase, i.e., from 770 kN to 1550 kN. The connection unit between the shield beam and the front link bears the maximum load, which rises from 3680 kN to 7610 kN. Specifically, the augmentation in load at this connection unit amounts to 3930 kN,

representing 1.07 times the load under a pressure of 2 MPa. The connection unit load of the shield beam's rear link increases by 3560 kN, i.e., approximately 1.04 times the load observed under a working pressure of 2 MPa. Conversely, the load pressure at the connection unit of the top beam remains low, with an increment of only 780 kN.

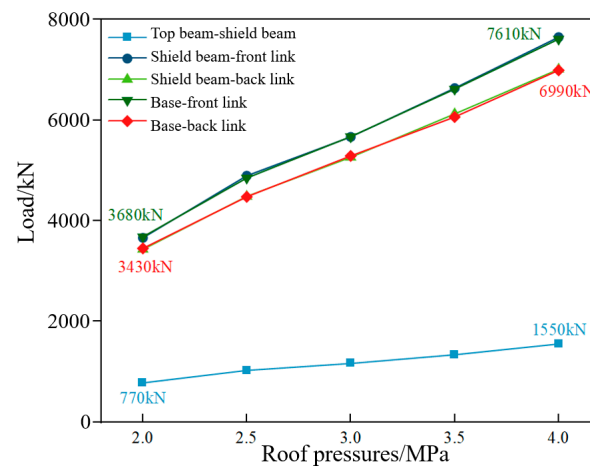


Figure 11. Loads of connection units under different roof pressures.

5. Analysis of Support Load Characteristics Under Different Loading Conditions

5.1. Loading Condition Analysis of Hs

This section is based on the 'General Technical Conditions for Hs (GB 25974.1-2010) [32]' to replicate the various conditions that an Hs may encounter during operation at a fully mechanized coal face. Five tests for assessing the strength of the Hs's main components were performed: (1) uniform loading at top beam, (2) loading both ends at the top beam, (3) front-end loading at the top beam, (4) back-end loading at the top beam, and (5) unilateral loading at the top beam.

Additionally, the uniform loading condition of the top beam under normal operating conditions was included, as illustrated in Figure 12. The Hs operated by loading the column with the support's rated working resistance of 17,000 kN. A load of 6000 kN was applied to the loading block at the front end of the top beam to ensure normal operation of the Hs. Lastly, a load of 11,000 kN was applied to the loading block at the back end of the top beam.

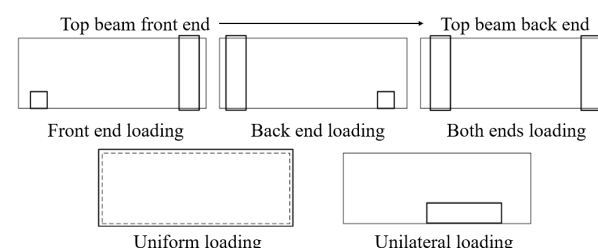


Figure 12. Schematic of top beam loading.

5.2. Uniform Loading at Top Beam Condition

The pressure distribution of each support component under uniform load and different mining heights is shown in Figure 13. The load pressure at the middle position of the support rib below the front column reaches a peak of 200 MPa, much higher than that at other positions. Consequently, under this loading condition, the rib plate of the front column of the top beam bears a relatively high load pressure. Moreover, the pressure at the rib plate and upper box of the connecting unit between the shield beam and the front connection unit is significant.

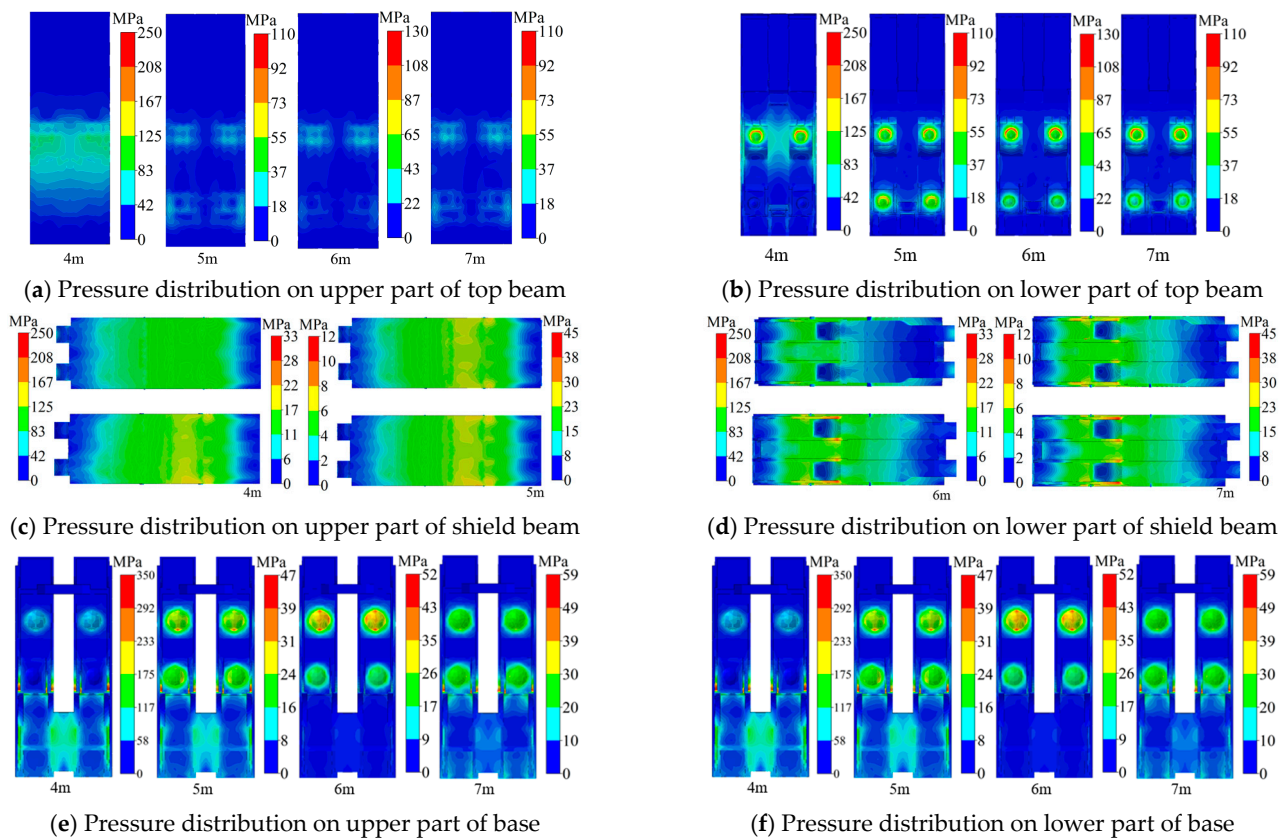


Figure 13. Pressure distribution of support components under uniform loading at top beam.

Regarding the numerical pressure value from 190 MPa to 42 MPa at a mining height of 4 m, the pressure zone at the connection unit of the shield beam–front link is weakened step-by-step to the shield beam’s middle, top, and back. An increase in the mining height reduces the pressure from 170 MPa at a 4 m mining height to 35 MPa at a 7 m mining height. The base pressure is predominantly focused on the arc transition position of the side guard plate due to torque. Moreover, the pressure value at the arc transition position diminishes as the mining height increases. Compared with the peak value of 220 MPa at a 4 m mining height, once the mining height reaches 7 m, the pressure value at the transition position is 14 MPa.

5.3. Condition of Loading Both Ends at Top Beam

The pressure distribution of each support component when loading both ends and with different mining heights is shown in Figure 14. The top beam bears a high torque, and a significant pressure concentration is formed at the arc transition position between the front guard plate and the rear end box. The pressure contour density is large, and the peak pressure reaches 820 MPa when the mining height is 4 m. The pressure at the front column socket of the top beam is weakened and divergent at both ends, reaching 200 MPa at a mining height of 6 m.

The pressure distribution trend of the shield beam varies under different mining heights. However, there is a large range of pressure concentration at the connection unit of the shield and top beams. The 4 m mining height is taken as an example. High pressure appears at the connection between the upper part of the shield beam and the connection unit. With propagation toward the central-right and left sectors, progressively attenuating as it extends from the front link connection unit at the right toward the base region and upper-left quadrant. Next, the pressure weakens and diffuses from the connection unit of the right front link to the bottom and the upper left side. The peak pressure is approximately

11 MPa. The pressure at the base's front column socket is elevated at various mining heights. Compared to other mining heights, the Hs experiences a pressure intensity of up to 50 MPa at a mining height of 4 m. The loading conditions at both ends significantly affect the top beam, whose peak pressure is significantly higher than that of other main structures.

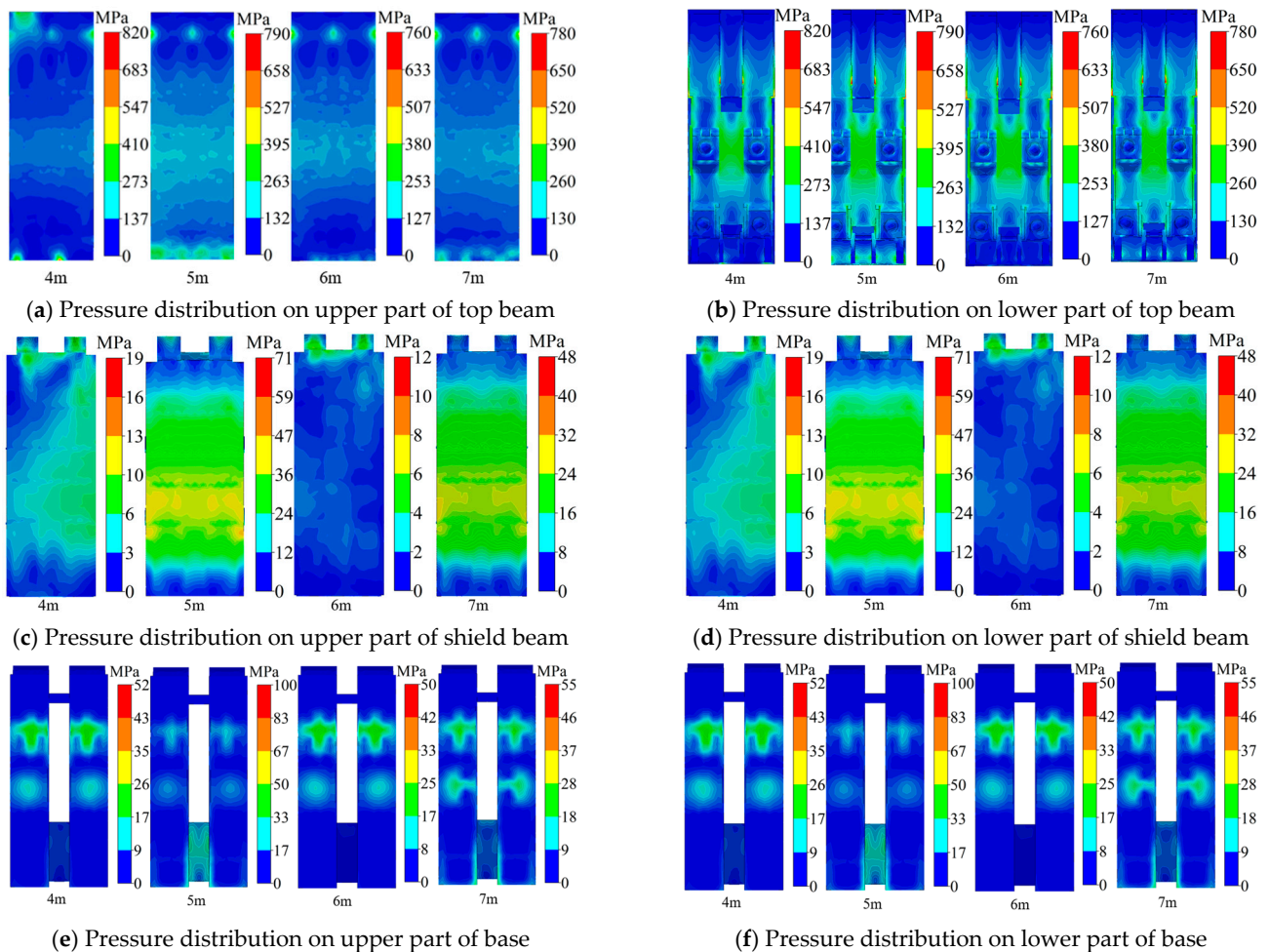


Figure 14. Pressure distribution of each component of support when loading both ends at top beam.

5.4. Condition of Front-End Loading at Top Beam

The pressure distribution of each support component under front-end loading conditions is shown in Figure 15. In this scenario, the top beam is subjected to torque in the horizontal and vertical planes. Consequently, a high-pressure zone spans from the front-end loading position along the left plate toward the front column socket area. As the mining height increases, the peak pressure rises from 1000 MPa to 1200 MPa. The shield beam presents a torsional bearing state under different mining heights. The pressure of the shield beam is concentrated on the left boundary, and it diffuses triangularly to the shield beam's upper right and back regions. The maximum value is approximately 120 MPa. A pressure concentration area develops at the arcuate transition point of the side guard plate on the loading side of the top beam's front end, with a maximum pressure of approximately 130 MPa.

5.5. Condition of Back-End Loading at Top Beam

The pressure distribution of each support component under back-end loading conditions and different mining heights is shown in Figure 16. An obvious pressure concentration trend can be observed at the connection between the loading position of the back end of

the top beam and the lower connection unit under the four mining heights. Moreover, the right-side pressure is higher than the left-side pressure. For example, when the mining height is 7 m, the right-side pressure reaches the maximum of 890 MPa. The left-side pressure concentration zone of the shield beam diffuses from the left-end boundary to the back and the left guard plate under different mining heights.

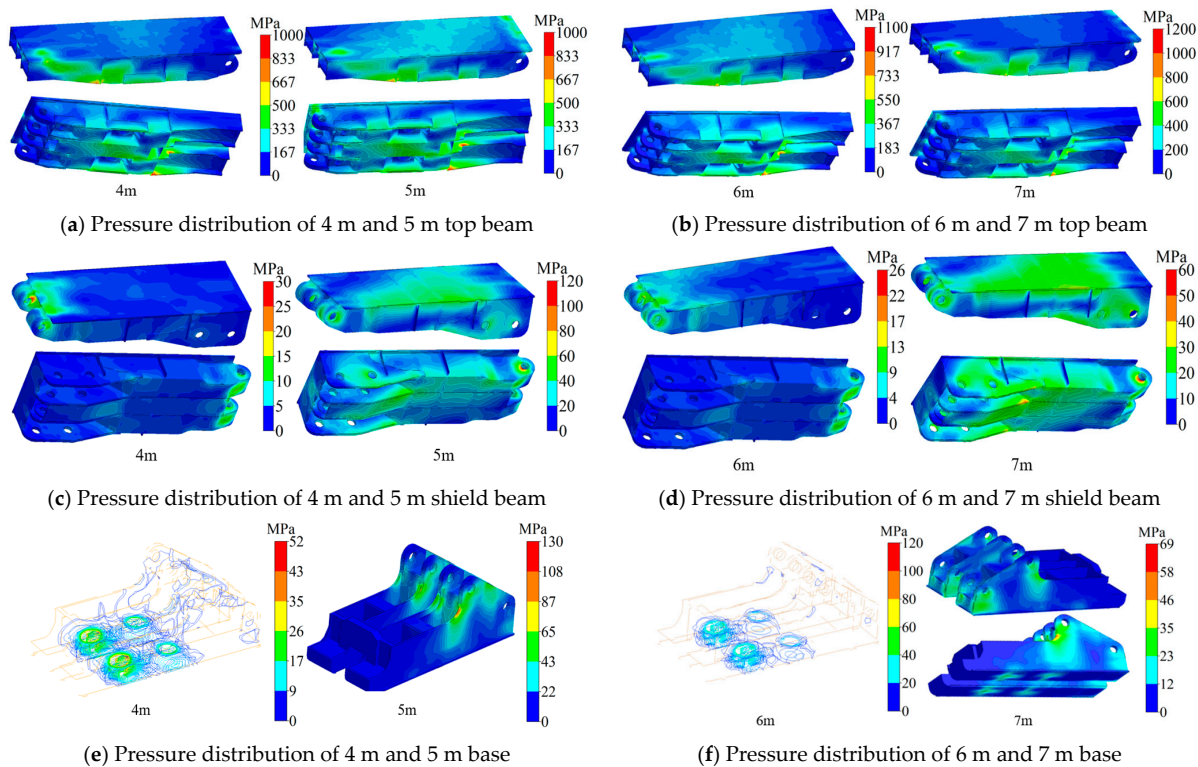


Figure 15. Pressure distribution of each component of support under front-end loading at top beam.

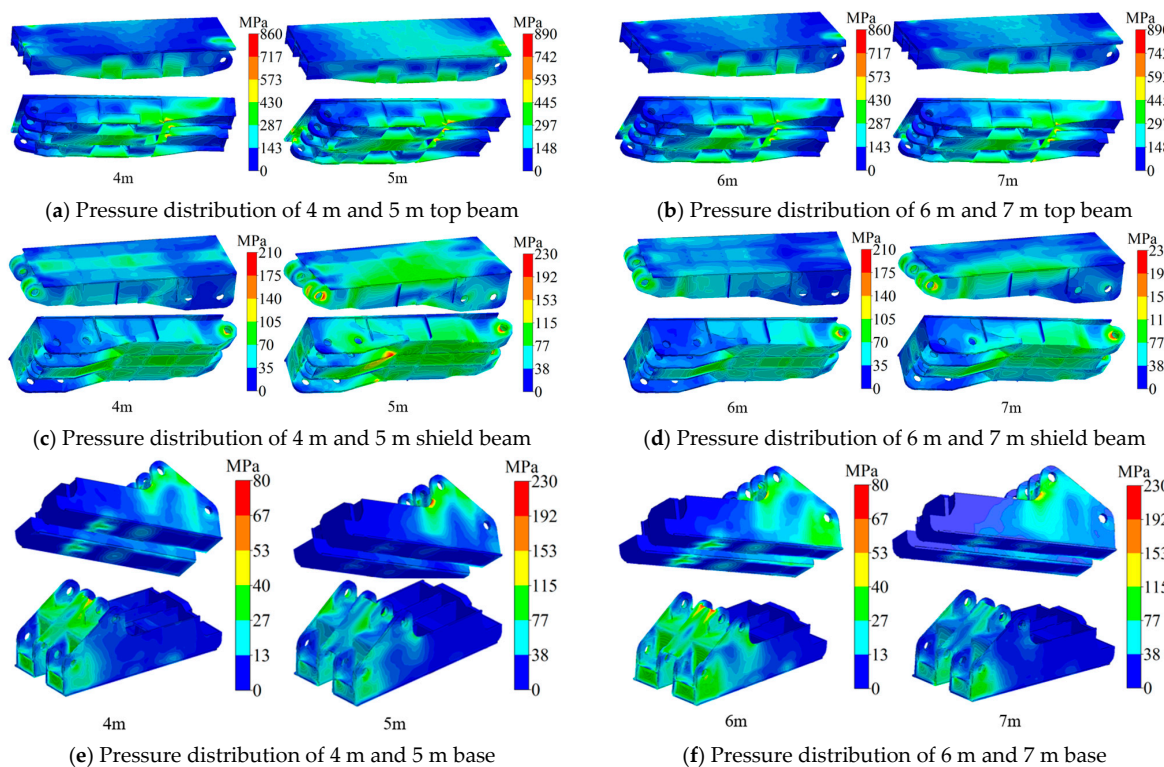


Figure 16. Pressure distribution of each component of support under back-end loading at top beam.

Moreover, the right-side pressure concentration zone extends from the right edge of the inner surface toward the inner surface and the right guard plate. A peak pressure of approximately 230 MPa emerges at the junction between the right support plate and the upper box beneath the shield beam. A significant pressure concentration area is present at the back of the base and the connection unit shaft hole of the side guard plate, with the pressure spreading along the side guard plate. The pressure is approximately 220 MPa at the four mining heights. For the Hs assembly, pressure intensities demonstrate negligible variation across structural components under eccentric loading conditions applied to the condition of back-end loading at the top beam. Lastly, the pressure change in the top beam is the most sensitive under this condition.

5.6. Condition of Unilateral Loading at Top Beam

The pressure distribution of each support component under unilateral loading conditions and different mining heights is shown in Figure 17. The loading position of the top beam and the central box are characterized by pressure concentration. The pressure values under four different mining heights were compared. It was found that the pressure reaches a maximum of 520 MPa when the mining height is 4 m. The pressure distribution of the shield beam is more balanced, showing a grid mesh distribution on the back of the shield beam.

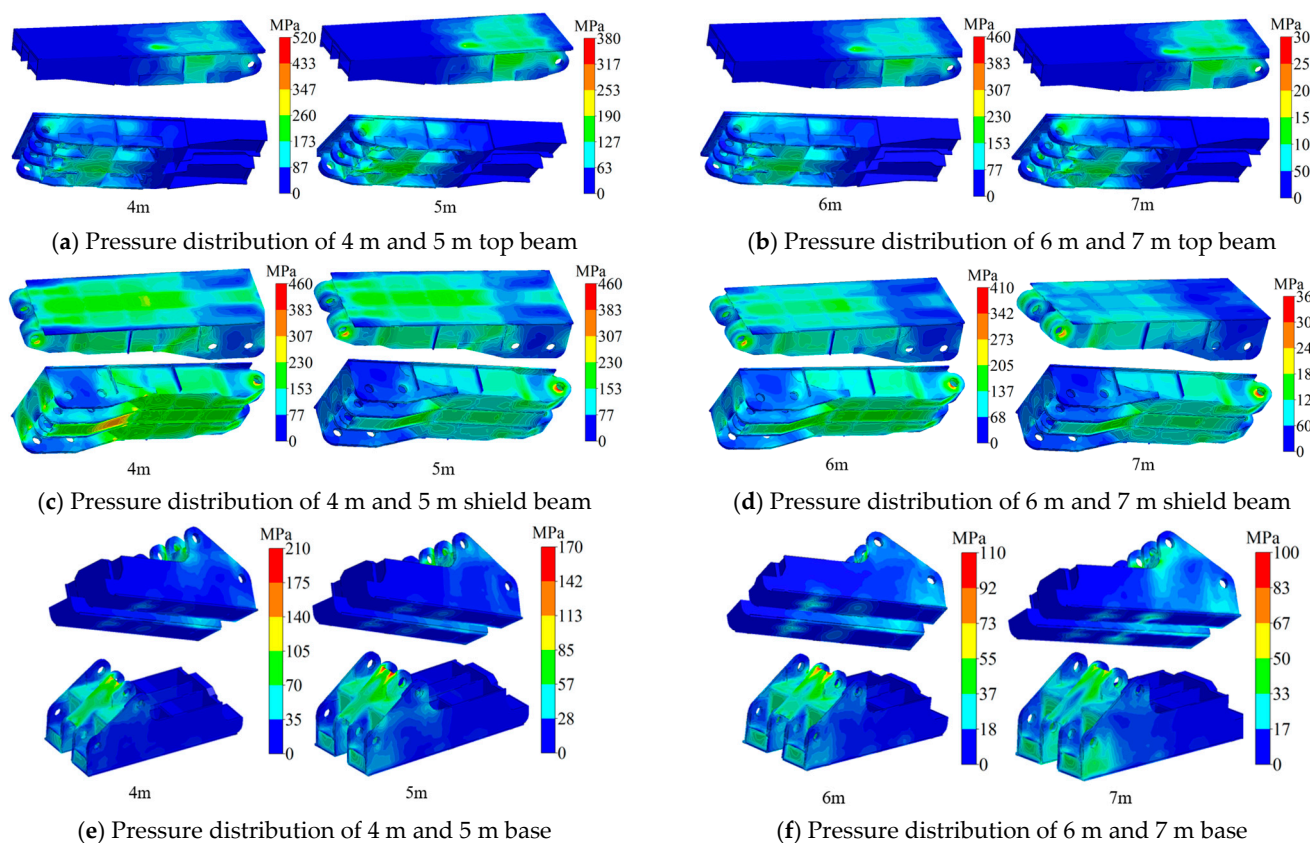


Figure 17. Pressure distribution of each component of support under unilateral loading at top beam.

In addition to the back end, there is a high-strength pressure distribution at the other positions. Moreover, the peak pressure is located on the coverage surface of the inner support guard plate. The 4 m mining height is taken as an example. The peak value of the back of the shield beam reaches 350 MPa. Once the support reaches the maximum height, the peak pressure of the shield beam is reduced to a minimum of 360 MPa. A large pressure in the bipedal connection plate structure of the base is observed, reaching a maximum of

210 MPa at a mining height of 4 m. A comparison of the bearing capacity of the Hs at different heights shows that the unilateral loading condition exerts the most significant impact on the stability of the Hs at a mining height of 4 m.

5.7. Analysis of Hs Connection Unit Characteristics Under Complex Working Conditions

The load bar chart of the connection unit of the Hs at various mining heights under complex loading conditions is depicted in Figure 18. The bearing safety of the support increases at heights of 5 m and 6 m when subjected to uniform loading, with a maximum load of approximately 478 kN. When loading is applied to both ends conditions, the connection unit difference between the two sides of the support reaches its maximum at a mining height of 4 m. A maximum difference of 104 kN is observed in the back link between the two sides. The load of each connection unit rises rapidly once the support reaches a 7 m mining height. The pressure exerted on the connection unit of the front link is 61 times greater than that at the 6 m mining height, amounting to 1270 kN. The connection unit of the Hs at a mining height of 7 m is significantly affected by the loading conditions at both ends. During front-end loading, the pressure applied to the connection units of the top beam and shield beam of the Hs is significantly higher than that on other connection units, when the mining height is between 4 and 6 m. The connection units on both sides of the support experience torsional loads, resulting in load differences that impact the lateral stability of the support.

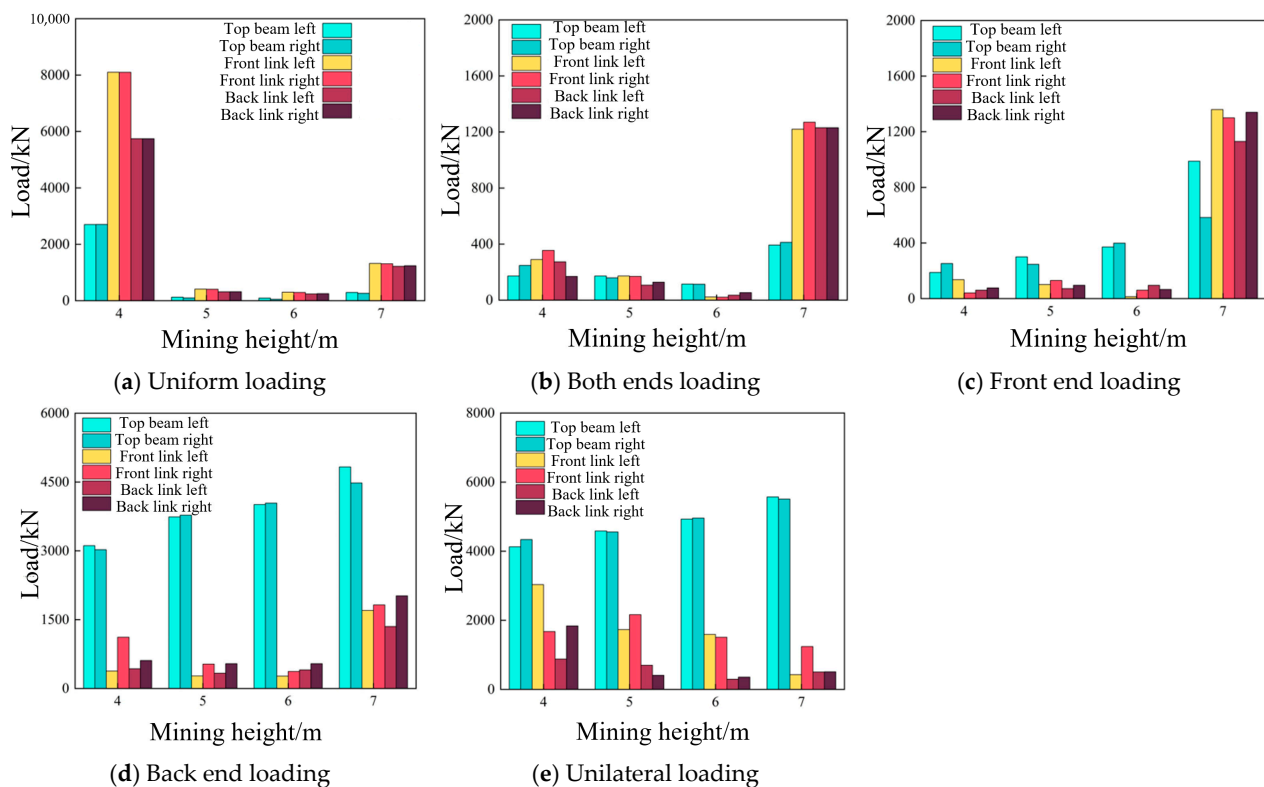


Figure 18. Histogram of connection unit loads under complex working conditions.

When a partial load is applied to the back end of the top beam, the connection load of the top beam–shield beam significantly exceeds that of other connection units. Specifically, the maximum load ratio compared to the connection unit of the front link is 15. Hence, under paranoid loading at the end of the top beam, the connection unit of the top beam–shield beam experiences excessively high bearing capacity, compromising the stability of the support.

When the support is under unilateral loading at the top beam, the connection unit load of the top beam–shield beam is the highest, followed closely by the front link. Specifically, the maximum load at the connection unit of the top beam–shield beam reaches 5570 kN. Additionally, the connection unit load difference between the two sides of the front link is the most significant at a mining height of 4 m, with a discrepancy of 1360 kN. In conclusion, the connection unit of the top beam–shield beam is the most susceptible to the offset loading condition. Under these five load distribution situations, this structure bears the highest average load, significantly impacting the safety and stability of the support.

6. Conclusions

In order to obtain the influence of different mining parameters on collaborative bearing characteristics between the Hs and surrounding rock coupling system, a dynamic analysis model of the coupling system was established in this work. The dynamic response laws of the coupling system under different mining heights, roof pressures, and loading conditions are discussed. The results show that with the increase in mining height, the load pressure of the support deteriorated sharply, the confining pressure significantly increased, and the pressure concentration phenomenon became more prominent. The following are the main conclusions of this work:

- (1) Under the same load, the displacement difference between the head and back of the top beam is 10.6 mm at a 4 m mining height; the difference is 21.1 mm at a 7 m mining height. As the height rises, the ‘raised’ trend of the Hs worsens, and the peak pressure between the base and the floor gradually shifts backward.
- (2) As the height rises, the peak pressure of the top beam of the Hs shows a downward trend; the peak pressure of the top beam of the support is 150 MPa when the mining height is 4 m, and 80 MPa when the mining height is 7 m. In contrast, the load at the connection unit shows a significant upward trend. The connection unit between the front link of the support and the shield beam increases most significantly with the height of the Hs, i.e., from 810 kN to 3240 kN. This increase brings greater challenges to the load of the connecting unit between the support and the link.
- (3) The pressure distribution of the ‘support–surrounding rock’ system is less affected by changes in roof pressure. In contrast, the maximum value of the system exhibits a positive correlation with the roof pressure. When the confining pressure of the roof increases from 2 MPa to 4 MPa, the peak pressure of the support increases from 180 MPa to 350 MPa. Consequently, the roof and floor pressure steadily increase from 15 MPa to 32 MPa.
- (4) The pressure distribution at the arc transition of the side guard plate of the main structure of the support is relatively concentrated under different load conditions. Therefore, the structure is prone to torsional deformation. Furthermore, as the loading condition of the support changes, the top beam–shield beam connection unit shows a higher average load response. The maximum pressure on the top beam reaches 5570 kN under unilateral loading conditions. Hence, it is advisable to avoid operating the top beam of the Hs under such loading conditions.

These studies have found that under complex loading conditions, pressure is significant at the arc-shaped transition of the side guard plate of the support’s main structure, and the load on the connection unit between the top beam and the shield beam of the support is relatively high. Therefore, in the subsequent support design, it is necessary to strengthen the above two aspects to ensure the stability and reliability of the support during operation. Due to computational efficiency constraints, this study adopted a coupling model of a single Hs and surrounding rock for mechanistic analysis. Future investigations will incorporate

multi-support configurations and introduce mining conditions from adjacent working faces to expand the generalizability of the research framework.

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