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Article

Design of a Highly Adaptable Advance Support for a Deep, Fully Mechanized Roadway and Analysis of Its Support Performance

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Abstract: Considering the harsh environment of deep, fully mechanized working faces and the acutely imbalanced time distribution among excavation, support and anchoring, this paper designed a new type of highly adaptable advance support for fully mechanized roadways that boasts high adaptability, great support strength and a large working space. Firstly, the structure composition and working principle of the advance support were introduced. The structures and mechanical characteristics were then emphatically discussed. Subsequently, with the geological conditions of the 8224-machine roadway in the XT Coal Mine taken as an example, the loads of the advance support were obtained and then imported into the Ansys software to obtain the stress distribution and displacement distribution of the whole advance support and its parts through calculation. Based on the distribution, the stress and strain of the advance support were analyzed. The simulation results are as follows: Under various working conditions, the maximum displacement of the advance support was 4.5 mm, which is negligible compared to the overall size of the support; the maximum stress was 72.8 MPa, which is lower than the yield strength of the material (235 MPa). Therefore, the designed support can bear the pressure from the surrounding rock in the mine. Moreover, the roof beam, which is a weak link in the support, deserves more attention in subsequent engineering designs. This method conduces to not only parallel operations of excavation, support and anchoring, but also to rapid excavation and the safe production of roadways, providing fresh ideas for the advance support for fully mechanized roadways.

Keywords: fully mechanized roadway; high adaptability; advance support; support design

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1. Introduction

As the main energy source in China, coal accounts for over 60% of China's energy consumption [1]. However, mining and excavation are the most dangerous production links during coal exploitation, and the fully mechanized working faces turn into accident-prone areas in coal mines [2]. Furthermore, gas, water, dust and other factors pose threats to worker safety. The environment is extremely tough [3,4]. The continuously increasing depth of coal exploitation leads to greater difficulty in coal mining. In addition, deep mining, especially the mining of deep coal seams with large dip angles, has encountered increasingly severe problems [5,6]. In such seams, poor stability of the roadway-head surrounding rock, harsh environment, small working space and difficult support result in slow excavation, which seriously imbalances the time distribution during excavation, support and anchoring, critically affecting the speed of roadway excavation [7–12]. Thereby, it is of great urgency to expand advance-support equipment for deep, fully mechanized roadways [13–17] so as to ensure parallel operations of excavation, support and anchoring and to improve excavation efficiency while guaranteeing the roadway construction safety.

In recent years, many scholars have conducted considerable research on the advance support for fully mechanized roadways. Hao et al. [18] established the vibration-mechanics model of advance support in the full-support state and performed vibration tests. Yu et al. [19] divided the deformation and failure evolution of the trend of abandoned roadway roofs into four stages: initial deformation, bending-separation deformation, fracture failure and collapse failure. The technology for filling and controlling the trend of abandoned roadways, with high-water material over the fully mechanized mining face, was proposed, and the effect of the filling body on the roofs of the abandoned roadways was revealed. Juarez et al. [20] studied the stability and strength of the column cylinder of the self-moving advance support by means of simulation. Based on the simulation results, they analyzed the stress and deformation of the roof beam and the main beam of the support. Xie et al. [21] adopted a grouting anchor cable (bolt) + U-type steel + a single-prop-combined support technology to support the roof, and on this basis, proposed grouting the anchor cable to reinforce the weak surface of the roof and plug the cracks. In order to enhance the stability and safety of the advance support for roadways during stepping advancement, Wang et al. [22] formulated a control method for stable stepping advancement, in accordance with the principle of the average hydraulic-oil volume release. Meanwhile, they constructed a prototype of a similar test model with a compression ratio of 1:8 and developed a test platform and a measurement datum frame for simulating the roadway roof. In this way, the mechanical tests were carried out on the coupling system of the roof and the advance support. Given the problems of untimely support, low support strength and labor-consuming and time-consuming processes that exist in the current mode of advance support for mechanized roadways, Zhang et al. [23] developed a new set of stepping self-moving advance supports. Considering that the advance support for mechanized roadways faces the problems of long support time, poor quality and low strength, Sochacki et al. [24] designed a set of self-moving advance-support equipment and performed mechanical analysis, numerical simulations and field tests. To sum up, the existing studies demonstrated that current advance-support equipment of fully mechanized roadways confront many problems, such as complex processes, slow movement, low work efficiency, high labor intensity, difficult roof management and poor adaptability, failing to ensure safety.

On this basis, taking the excavation project of the 8224-machine roadway in the XT Coal Mine as the background, this paper designed a new type of highly adaptable advance support (HAAS) for fully mechanized roadways. The advance support integrated the functions of support, movement and protection. The movement mechanism of the support was set in the middle of the column so as to realize the fast and flexible movement of the support. Meanwhile, the column of the support was telescopic and hinged with the roof beam, which adapted to the floor undulation of the roadway and the change in roof-dip angles. Moreover, the structure and working principle of the key components of the equipment, i.e., the advance support, were elaborated. Finally, the stress and deformation under different working conditions were also analyzed. The analysis results provide technical support for the advance support for fully mechanized roadways.

2. Characteristics of the Structure of HAAS for Deep, Fully Mechanized Roadways

2.1. Structure of the Support

The new type of HAAS for fully mechanized roadways consists of the metal structural parts and the hydraulic system. As shown in Figure 1, the maximum structural height, the maximum stretching length and the maximum working resistance are 3.6 m, 7.9 m and 1600 kN, respectively. In addition, the metal structural parts are divided into the front group and the rear group. During movement, the two groups support, push and pull each other. They take hydraulic pressure as the power and the girders on both sides as the guidance, which is conducive to fast and flexible movement and large-scale support.

(**a**) Front view (**b**) Side view

Figure 1. Schematic diagram of the new type of HAAS for fully mechanized roadways.

2.2. Working Principle of the Support

The new type of HAAS for fully mechanized roadways coordinates with devices such as roadheaders and anchor-drilling machines during roadway excavation. In addition, it mainly completes the actions of column lifting and lowering, movement and support under the control of the hydraulic control system, and the advance support can realize rapid movement and large-scale support. The specific working state is as follows.

(1) After the roadheader finishes a cutting, under the control of the hydraulic system, the column cylinder of the front support contracts. In this way, the lower column rises, while the upper column falls. Ultimately, the column of the front support separates from the roof and the floor (Figure 2a).

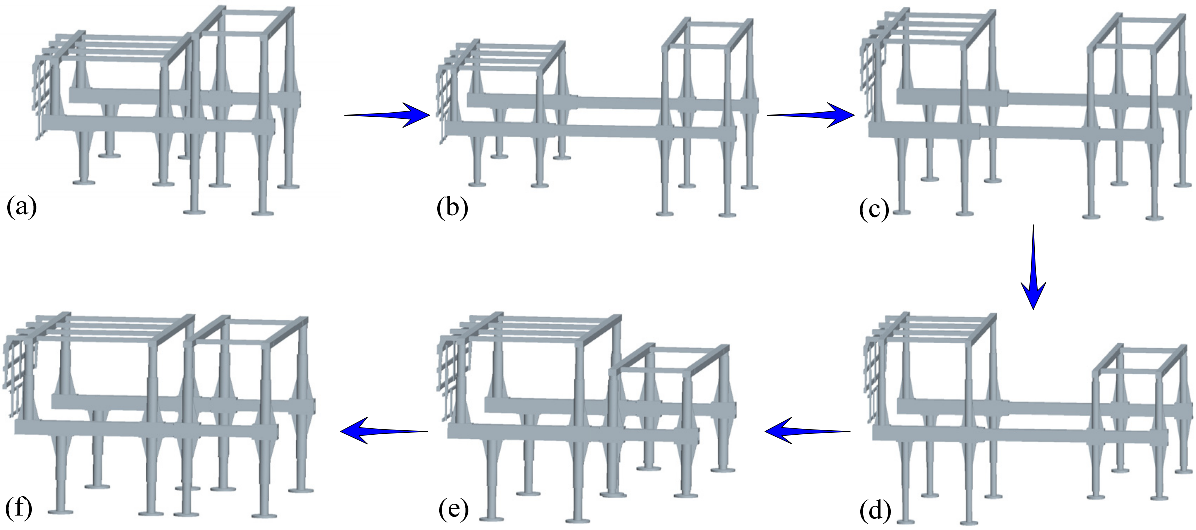


Figure 2. Working process of the new type of HAAS for fully mechanized roadways. (**a**) Support preparation; (**b**) Front support movement; (**c**) Front support expansion; (**d**) Rear support retracted; (**e**) Rear support movement; (**f**) Rear support expansion.

(2) Then, the column cylinder of the front support maintains the contraction state. During this process, the advance support underpinned by the rear support pushes the front one forward to the target position with the aid of the hydraulic system (Figure 2b).

(3) While the front support moves to the target position, its column cylinder extends through the hydraulic system. Subsequently, the lower column falls to the floor, and the upper column rises to the roof, thus completing the support for the roof (Figure 2c).
(4) The column cylinder of the rear support contracts under the control of the hydraulic system. Thus, the lower column rises, while the upper column falls. Ultimately, the column of the rear support separates from the roof and the floor (Figure 2d).
(5) The column cylinder of the rear support maintains the contraction state. Meanwhile, through the hydraulic system, the advance support underpinned by the front support pushes the rear one forward to the position nearest to the front support (Figure 2e).
(6) The column cylinder of the rear support extends with the assistance of the hydraulic system. By doing so, the lower column of the rear support falls to the floor, and its upper column rises to the roof. As a result, a whole movement process of the advance support is completed (Figure 2f).

In this way, whenever the roadheader performs an excavation for a certain distance, the new type of HAAS simultaneously advances for a corresponding distance in an alternating way, closely following the roadheader. The specific working state provides timely support for the newly exposed roof after the roadheader excavation and prevents the loosening and caving in of the roof. Furthermore, it improves the support conditions of the end of the roadheader and effectively protects the safety of equipment and personnel. Additionally, the utilization of the hydraulic support for excavation not only leaves relatively sufficient space for parallel operations of multiple anchor-drilling machines, but also reduces support time, thus creating conditions for the rapid advance of the working face. If the floor undulates, the lower column of the support will be adjusted to a different floor-touching height; if the roof inclines, the upper columns on the left and right sides of the support will be altered to different roof-connecting heights. Hence, the new type of HAAS preferably accommodates the floor undulation of the roadway and the change in roof-dip angles.

2.3. Technical Characteristics of the Support

Technical characteristics of the new type of HAAS for fully mechanized roadways are shown as follows.

(1) Novel structural design

The new type of HAAS, which is controlled by the hydraulic system, is characterized by convenient operation and control, low inertia of motion of the whole structure and rapid reaction speed. In addition, the support is able to realize self-advance, perform other various actions and be easily automated. The movement mechanism of the support is arranged in the middle of the column. With such an arrangement, the front support and the rear support push and pull each other, thus avoiding disadvantages caused by the arrangements along the roof and the floor in mechanized roadways. Moreover, as the whole structural frame of the support is relatively large, the roadheader can conduct operations under the complete coverage from the support.

(2) High adaptability

The columns are hinged with the roof beam. In this way, the columns on both sides, by adjusting themselves to different heights, are applicable to the roadway with an inclined roof, whose maximum dip angle reaches 15°. Since the telescopic columns of the support directly contact the roadway floor, the support is also suitable for roadways with an undulating floor. In addition, the maximum working resistance of the support is 1600 kN, enabling the support to provide greater supporting force and to serve roadway excavation with high roof loads.

(3) High level of safety and reliability

The new type of HAAS actively supports the roadway roof inside the empty roof area through the extension of the front probe beam. This indicates significant progress in safety compared with traditional passive-support methods, such as temporary supports with the capped ore column or with the front probe beam. Moreover, the great support strength and working resistance of the support further enhance its safety and reliability. The designed length of the support ranges from 5500 mm to 7900 mm. In such an environment, with abundant working space and high safety, workers can set anchor bolts (cables) under the protection of the hydraulic support.

(4) High excavation efficiency

The new type of HAAS adopts the hydraulic system, which endows it with the ability of rapid movement. This ability facilitates the advance of the working cycle during roadway excavation. Moreover, the long step distance of support movement improves the circulating footage and significantly reduces the time spent in temporary support, thereby remarkably promoting excavation efficiency. In addition, the advance support with a simple structural design can be run by only one person, while the traditional temporary support with front probe beam needs to be operated by at least three to four people. Consequently, the new type of HAAS saves working space and contributes to the improvement of the overall excavation efficiency.

3. Coupling Dynamic Model of the Advance Support and the Roof

According to the relationship between the advance support and the roof, the coupling dynamic model of the advance support and the roof is constructed in the light of the theory of overburden rock mass block (Figure 3). The following assumptions are made: m_s is the equivalent mass of the advance support; k_s, c_s and z_s are the support stiffness, damping and vertical displacement of the advance support, respectively. The roadway roof is composed of countless overburden rock mass blocks. The mass and vertical displacement of each overburden rock mass block are $m_i(i = 1, 2, \cdots, n)$ and $z_i(i = 1, 2, \cdots, n)$, respectively. The rocks, which have a higher stiffness than the soft and loose structures between the rock, are regarded as rigid bodies. In contrast, the soft structures between the rocks are viewed as the viscoelastic Kelvin solid. Moreover, the elastic coefficient is $k_j(j = 1, 2, \cdots, n-1)$ and the damping coefficient is $c_j(j = 1, 2, \cdots, n-1)$. k' and c' act as the stiffness and damping of contact between the advance support and the roof. As the rocks exhibit viscoelastic properties, their vertical displacement is $\delta_i(i = 1, 2, \cdots, n)$ [25].

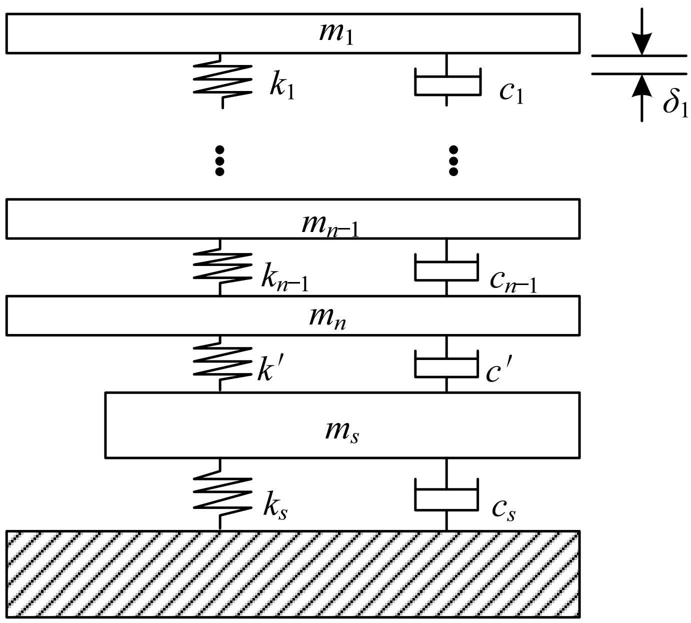


Figure 3. Simplified two-dimensional graph of the dynamic model of coupling between the advance support and the roof.

The coordinate origin of the dynamic model of the coupling system is seen as the static equilibrium position of the rock system. Through analysis of the static equilibrium position, the differential equation of the coupling dynamic response between the advance support and the roof is obtained [26]:

$$M\ddot{z}(t) + C\dot{z}(t) + K[z(t) + \delta] = Mg \tag{1}$$

where M, C and K are the mass matrix, damping matrix and stiffness matrix of the system, respectively.

$\ddot{z}$ is the acceleration vector of rock blocks;
$\dot{z}$ is the velocity vector of rock blocks;
z and δ are the displacement vector of rock blocks and viscoelastic fixing between rock blocks, respectively. $z = [z_1, z_2, \cdots, z_n, z_s]^T$, $\delta = [\delta_1, \delta_2, \cdots, \delta_n, \delta_s]^T$;
and g is the acceleration of gravity.

The expressions of the mass matrix, damping matrix and stiffness matrix of the system are demonstrated as follows:

$$M = \begin{bmatrix} m_1 & & & & \\ & m_2 & & & \\ & & \vdots & & \\ & & & m_n & \\ & & & & m_s \end{bmatrix} \tag{2}$$

$$C = \begin{bmatrix} c_1 & -c_1 & & & & & \\ -c_1 & (c_1 + c_2) & -c_2 & & & & \\ & \ddots & \ddots & \ddots & & & \\ & & -c_{j-1} & (c_{j-1} + c_j) & -c_j & & \\ & & & \ddots & \ddots & \ddots & \\ & & & & -c_{n-1} & (c_{n-1} + c') & -c' \\ & & & & & -c' & (c' + c_s) \end{bmatrix} \tag{3}$$

$$\mathbf{K} = \begin{bmatrix} k_1 & -k_1 & & & & & \\ -k_1 & (k_1 + k_2) & -k_2 & & & & \\ & \ddots & \ddots & \ddots & & & \\ & & -k_{j-1} & (k_{j-1} + k_j) & -k_j & & \\ & & & \ddots & \ddots & \ddots & \\ & & & & -k_{n-1} & (k_{n-1} + k') & -k' \\ & & & & & -k' & (k' + k_s) \end{bmatrix} \tag{4}$$

4. Stress Analysis on the HAAS for Deep, Fully Mechanized Roadways

4.1. Model Establishment

On the basis of the structure of the HAAS for deep, fully mechanized roadways, the three-dimensional model of the advance support is established by the Ansys software. The support material is Q235 steel, with a yield strength of 235 MPa, an elastic modulus of 200 GPa, a Poisson's ratio of 0.3 and a density of 7850 $\mathrm{kg/m^3}$. The regular structure of the roof beam of the advance support is displayed through the structured grid, while the rest parts are shown through the unstructured grid (Figure 4).

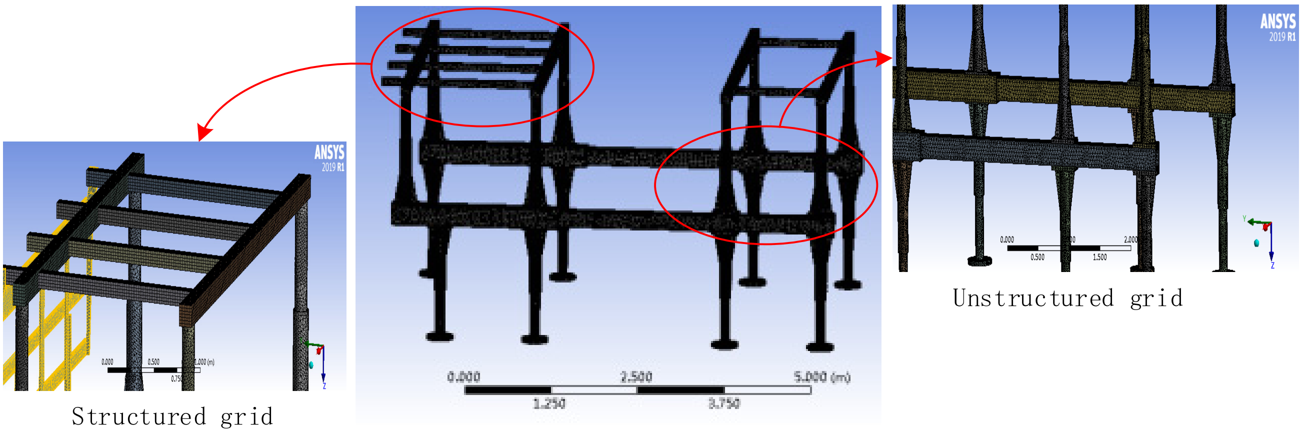


Figure 4. Overall finite element model of the advance support.

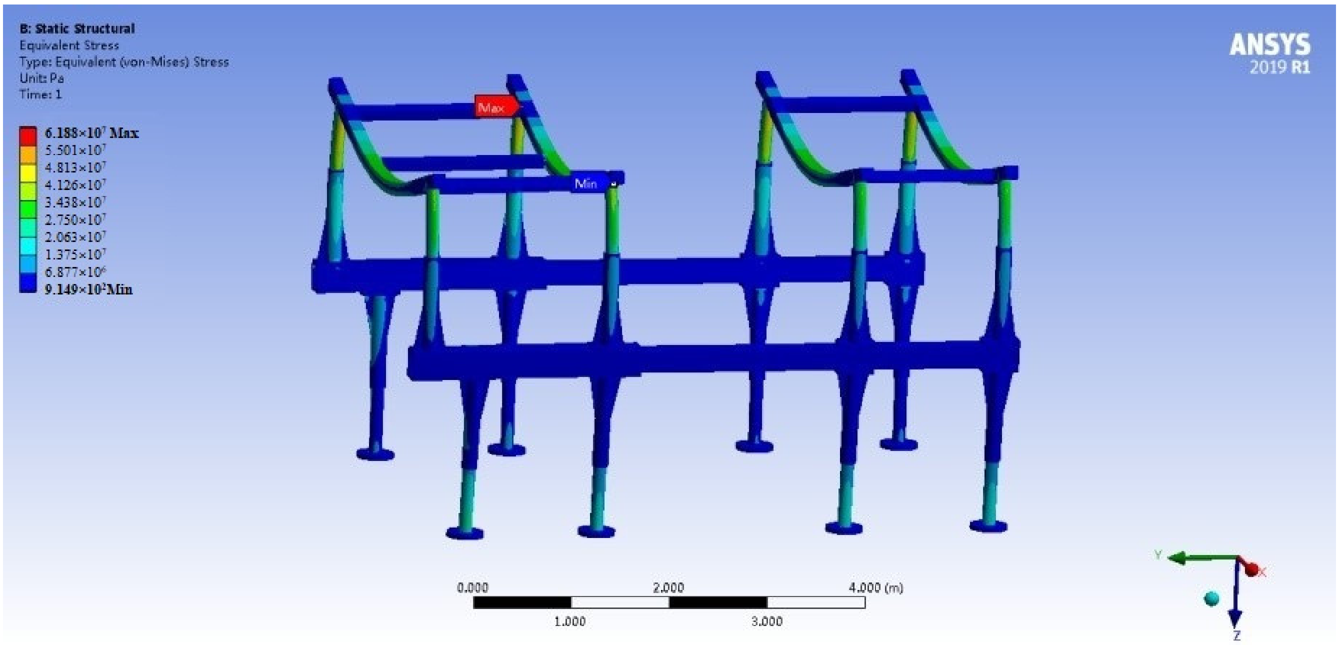
To obtain its working loads, the working state of the advance support was simulated according to the geological conditions of the 8224-machine roadway in the XT Coal Mine. In view of the working process of the advance support, the anchor bolts are set right after the support is unfolded and then contacted with the roadway. Correspondingly, the two sides of the roadway remain unstressed. Afterwards, the displacements of the base and the face guard are fixed and the roof beam of the support is subjected to 0.31 Mpa stress from the roof. Concurrently, gravity is imposed on the model of the advance support so as to implement simulation analysis on the working loads of the advance support under different working conditions, including the normal external loads, lateral external-force interference and different roof-dip angles.

4.2. Stress Analysis on the Advance Support under the Normal External Loads

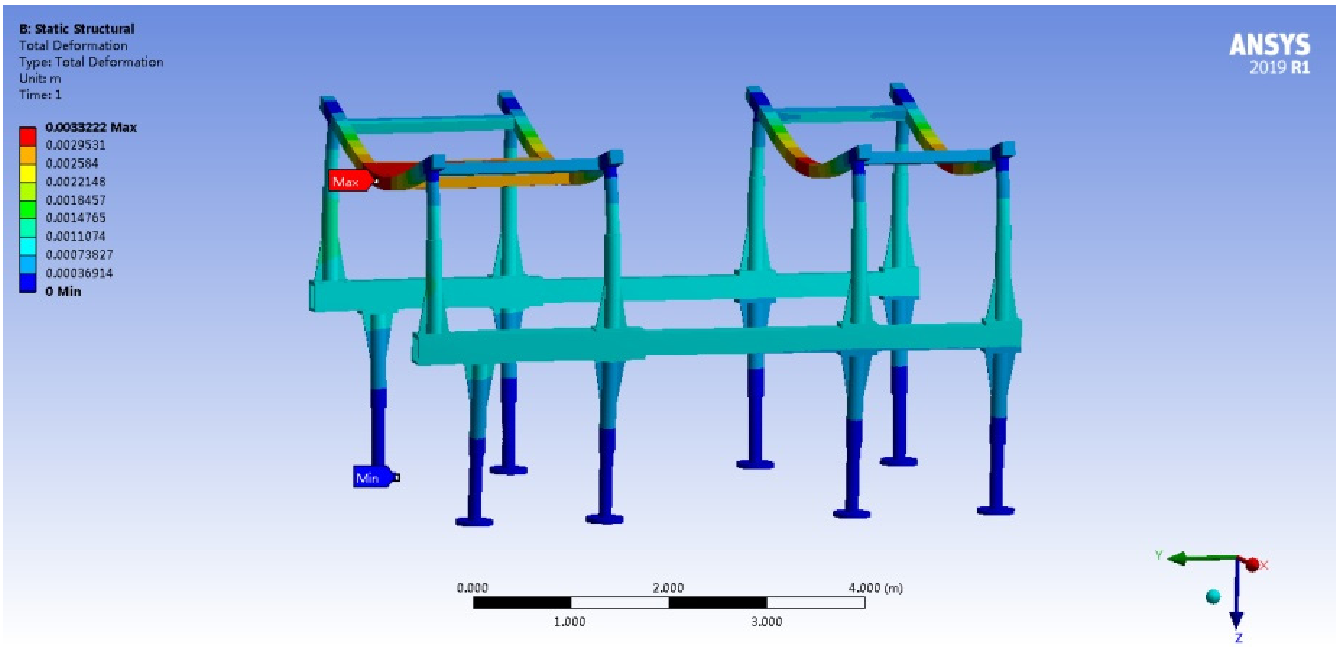
Under the premise of applying 0.31 Mpa external loads above the support, the overall stress and displacement distribution of the support under normal external loads are exhibited in Figure 5. As illustrated in Figure 5, the maximum stress of the support is 61.9 Mpa, which appears in the support column. The roof beam of the support also endures a relatively great stress of about 34.0 Mpa. Neither the stress of the support nor the stress of the roof beam exceeds the yield strength of the material (235 Mpa). Meanwhile, the maximum displacement (3.3 mm) of the support occurs in the middle of the roof beam. However, such a displacement is almost negligible compared to the overall length (4450 mm) of the roof beam. The maximum displacement of the column is relatively small (about 0.2 mm). Therefore, the roof beam is the comparably fragile component of the support. The results of the finite element analysis demonstrate that, under the influence of the normal external loads, the structure and strength of the overall support both meet the geological conditions of the 8224-machine roadway in the XT Coal Mine. In summary, the support is endowed with the ability to fulfill the task of a fully mechanized roadway support.

4.3. Stress Analysis on the Advance Support under the Lateral External-Force Interference

Considering that the support baffle may be subjected to the external force in the horizontal direction, the influence of the lateral external force on the stress and deformation of the support structure is investigated by directly applying this horizontal external force to the support. Therefore, by maintaining the normal working loads of the support, a horizontal force of 0.05 Mpa is imposed upon the front beam of the support and the ratio of the lateral external force to the longitudinal load is one-sixth. The overall stress and displacement distribution of the support under the lateral external-force interference are presented in Figure 6. As can be seen from Figure 6, the maximum stresses of the support are 72.8 Mpa, 10.9 Mpa or 17.6% higher than that in the absence of the lateral external force; the maximum stress appears on the inner column. In addition, according to the displacement distribution, the maximum displacement under the lateral force is 3.9 mm, increasing by 18.2% or 0.6 mm compared with that in the absence of the lateral external force; the maximum displacement occurs on the inner beam. By analyzing the influence of the lateral external force on the support, the following conclusions are drawn. The external force has an obvious influence on the beams and columns inside the support; the lateral loads and the vertical loads exert an equivalent impact on the whole support; the lateral external force wields a slightly greater effect on the maximum displacement of the support than the vertical stress.

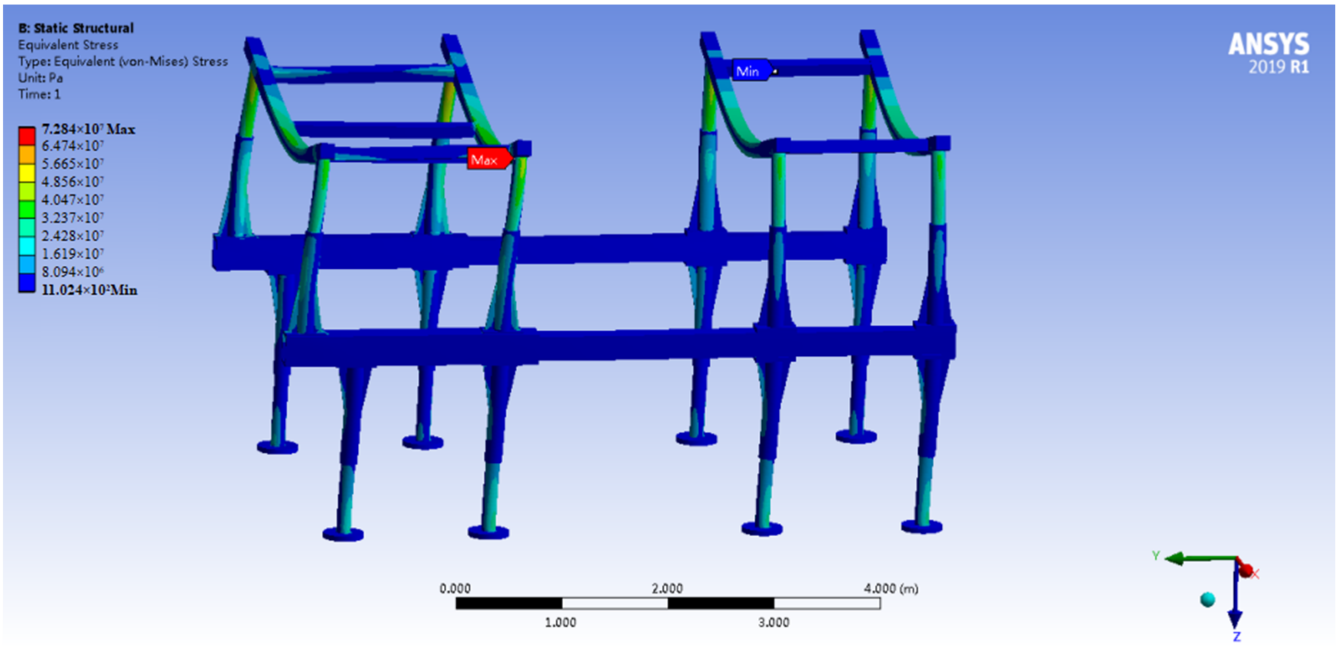


(**a**) Stress distribution

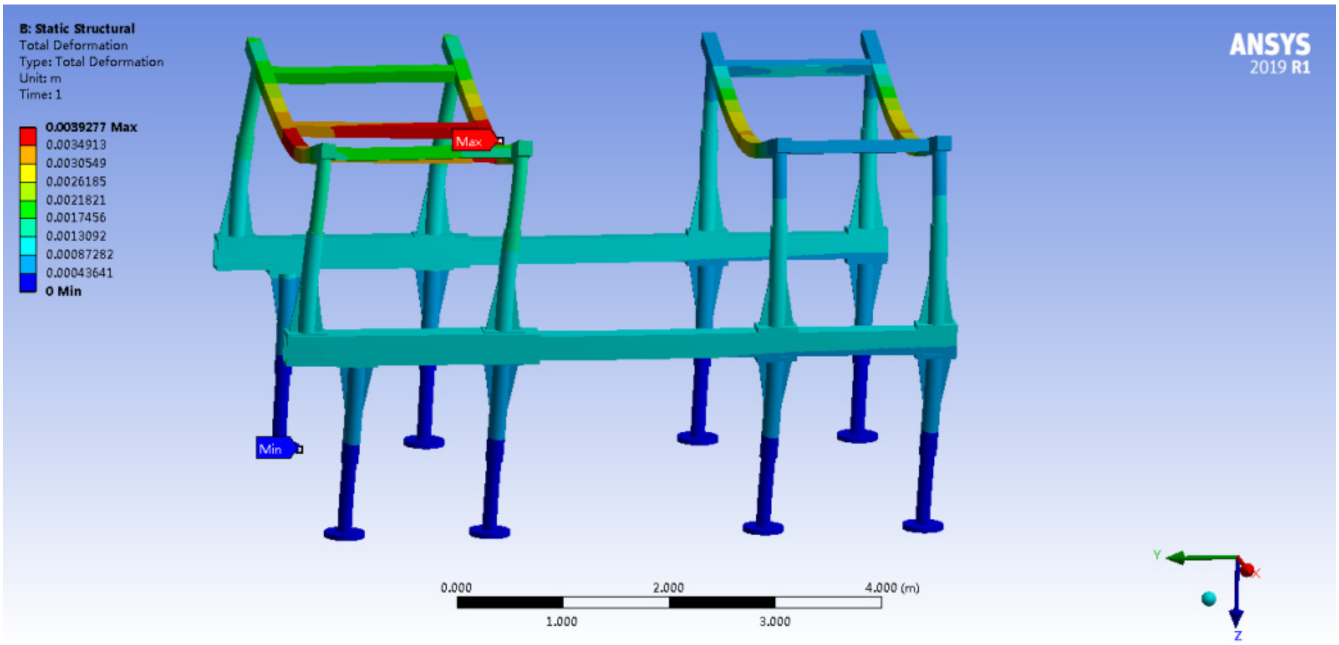


(**b**) Displacement distribution

Figure 5. Stress and displacement distribution of the advance support under the normal external loads.



(**a**) Stress distribution



(**b**) Displacement distribution

Figure 6. Stress and displacement distribution of the advance support under the lateral external-force interference.

4.4. Stress Analysis on the Advance Support under Different Roof-Dip Angles

Considering the adaptability of the support to different roof-dip angles of roadways, the support simulation schemes are arranged under different roof-dip angles, i.e., 0°, 5°, 10° and 15°. The overall stress and displacement distribution of the support under different roof-dip angles are shown in Figure 7. As can be observed from Figure 7, the maximum stresses of the support under different roof-dip angles all appear on the column and the maximum stress of the column rises with the increase in the roof-dip angle. When the roof-dip angle is 0°, the maximum stress of the support is 60.6 Mpa; when the roof-dip angle is 15°, the maximum stress of the support is 64.4 Mpa, growing by 6.27%, but still much lower than the yield stress of the material of 235 Mpa. Under different roof-dip angles, the maximum displacements of the support all occur in the middle of the beam and rise with the increase in the roof-dip angle. When the roof-dip angle is 0° and 15°, the maximum displacement of the support is 3.3 mm and 4.5 mm, respectively. Meanwhile, under the effect of roof loads, the column experiences a certain amount of outward offset. Moreover, with the increase in the roof-dip angle, the outward offset of the left high column presents a relatively huge rise. Such an outward offset of the support column is considerably unfavorable to the stability of the whole structure. Thus, in practical engineering applications, the roof-dip angle of a roadway should be kept within 15°, which is well-suited for the hydraulic support for excavation.

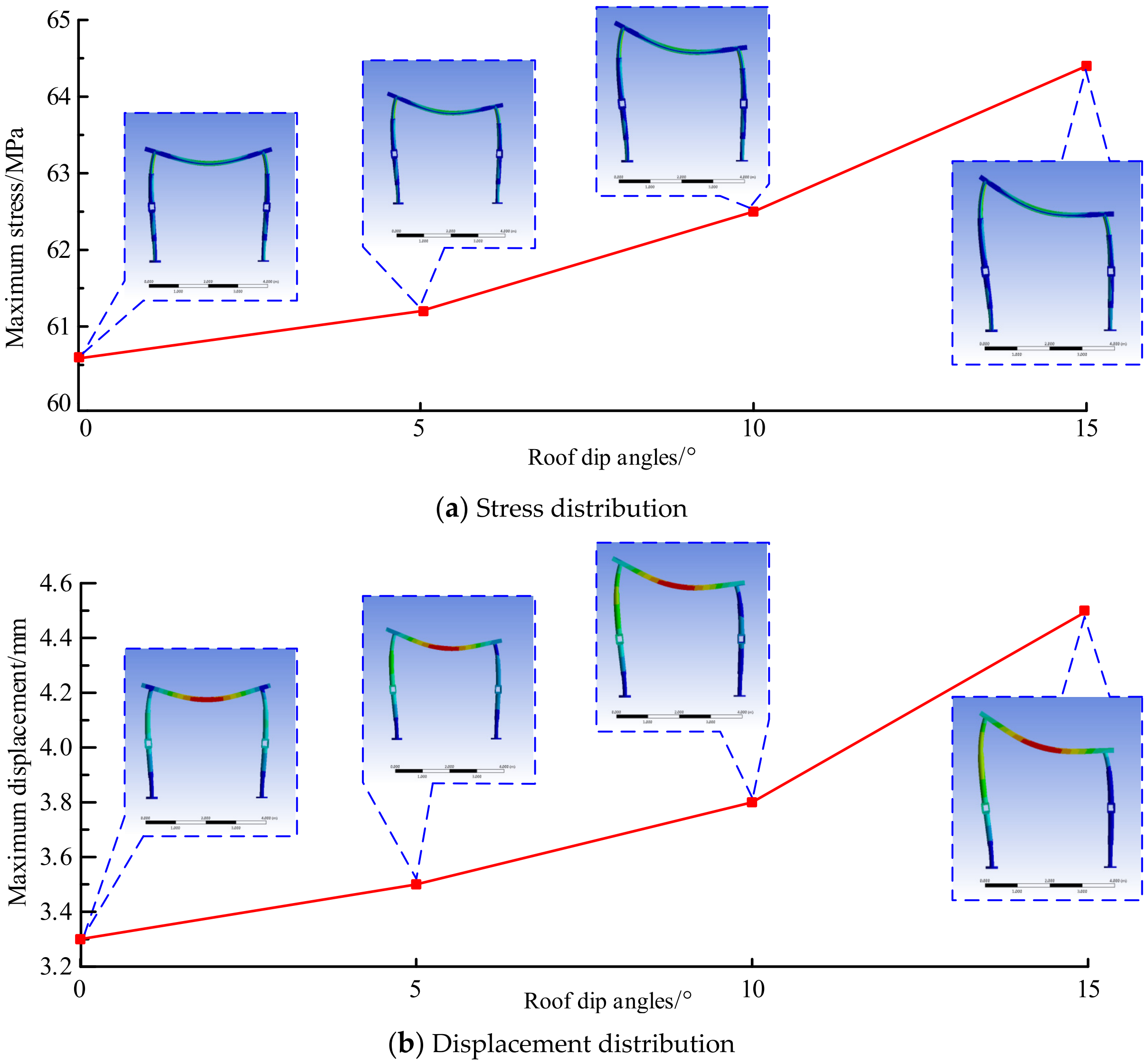


Figure 7. (**a**) Stress and (**b**) displacement distributions of the advance support under different roof-dip angles.

5. On-Site-Application Effect

The strike length of the $8_2$24-machine roadway in the XT Coal Mine is about 1547 m and the dip length is approximately 246 m (Figure 8). The stratigraphic column is shown in Figure 9. The HAAS for deep, fully mechanized roadways was officially installed in January 2018. During the trial excavation process from February to March, the stability tests for single-machine operations and multimachine linkage operations were implemented. The normal production began in April and the production capacity met the design requirements. The following is the site-application effect of the HAAS for deep, fully mechanized roadways.

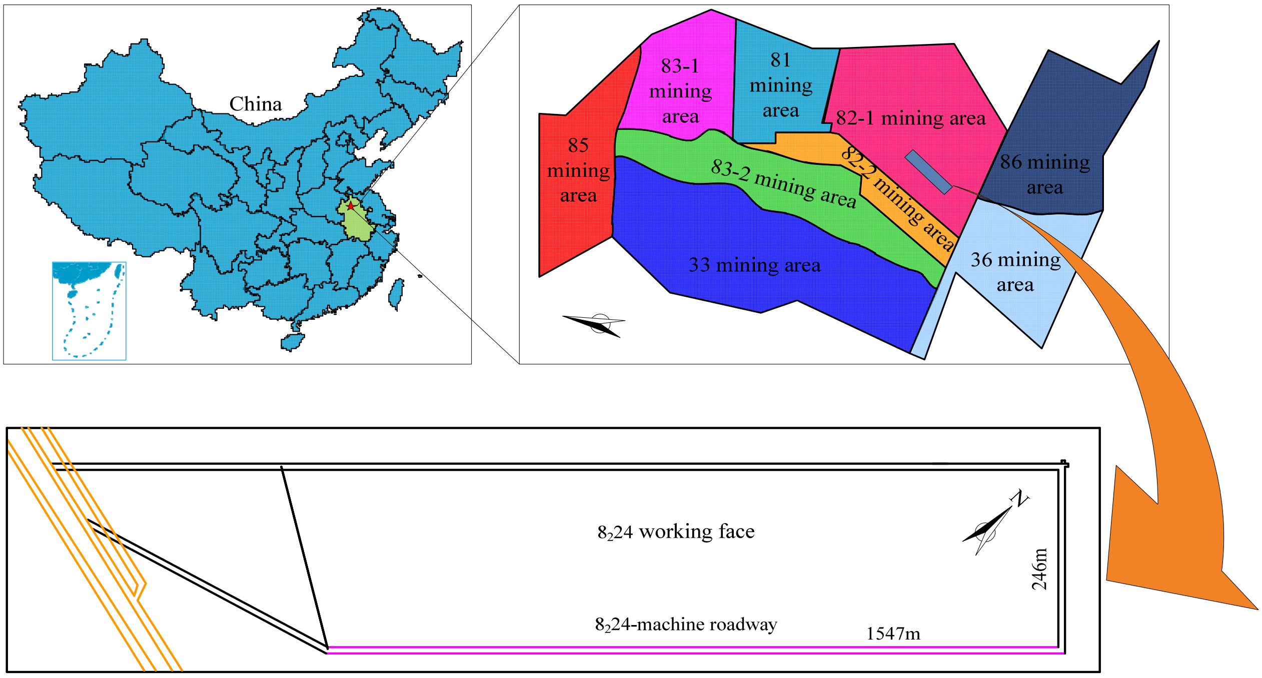


Figure 8. Location map of the $8_2$24-machine roadway in the XT Coal Mine.

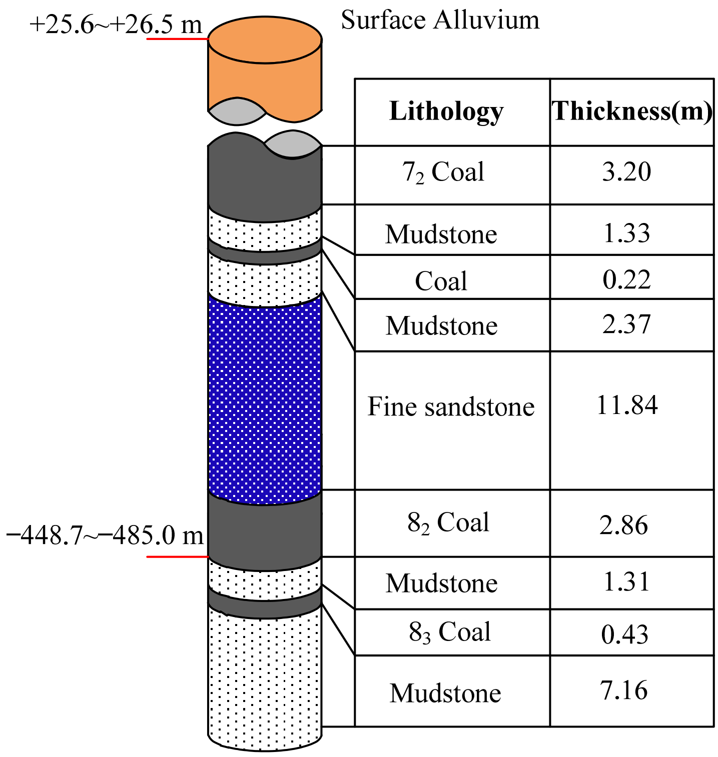


Figure 9. The stratigraphic column of the $8_2$24-machine roadway in the XT Coal Mine.

(1) Success in active support: Through the hydraulic system, the advance support successfully provides active support to the roof. The hydraulic support for excavation adopts the frame structure. Additionally, the overall structure of the support bears relatively large roof pressure, with high support strength and effective control of complex surrounding rocks.

(2) Wide coverage of the roof support: The hydraulic support delivers effective support to the roof within 6 m of the roadway head, leaving abundant safe space for operators in the roadway head.
(3) Success in remote control: The operators stand under the permanent support at the back of the advance support so that they can operate the hydraulic system away from the roadway head. In this way, they have no need to approach the roadway head or receive safety threats from the roof, thereby achieving intrinsic safety.
(4) High adaptability of the support: Since the support is well-adapted to changes in the roof-dip angles and roadway slopes, it can be widely used in various roadways with complex conditions.
(5) Improvement of the working cycle: Compared with traditional temporary supports, the hydraulic support with a long step distance extends the working cycle from 1.6 m to 3.2 m, which greatly boosts the single heading level of roadway excavation.
(6) Improvement of support efficiency: The support with low labor intensity is run by only one person. It performs continuous operations of excavation and support. By using support for an extensive cover, the parallel operations with two anchor-drilling machines are now implemented by four machines, greatly improving the efficiency of roadway support.

6. Conclusions

(1) The structure of HAAS for deep, fully mechanized roadways was preliminarily designed. The support arranged the movement mechanism in the middle of the column so as to achieve rapid and flexible movement. Simultaneously, the telescopic support column was hinged with the roof beam, adjusting to the floor undulation of the roadway and the change in the roof-dip angle.
(2) The finite element model of HAAS for deep, fully mechanized roadway was established and the stress and displacement distribution of the advance support under different working conditions were obtained by calculation. The analysis results showed that the support designed for various working conditions bears the pressure from surrounding rocks without being destroyed, which meets the requirements of fully mechanized roadway support. In addition, the relatively great stress and deformation are generally located at the roof beam and column of the support. Factors such as lateral external force and roof-dip angle have a great influence on the support stability.
(3) The on-site application of the $8_2$24-machine roadway in the XT Coal Mine revealed that the HAAS for deep, fully mechanized roadways effectively controls the roof stability. The support also eliminated the difficulty in support movement and enhanced the excavation efficiency of the fully mechanized roadway, saving the costs of manpower and material resources. In addition to notable economic benefits, it also boasts remarkable social benefits, as it improves the working environment of the working face, reduces the labor intensity of workers and resource waste, and achieves the technical progress of intelligent mining in coal mines.

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References

1. Wang, Q.; Jiang, Z.; Jiang, B.; Gao, H.; Huang, Y.; Zhang, P. Research on an Automatic Roadway Formation Method in Deep Mining Areas by Roof Cutting with High-strength Bolt-grouting. *Int. J. Rock Mech. Min. Sci.* **2020**, *128*, 104264. [CrossRef]
2. Ma, P.; Qian, D.; Zhang, N.; Shimada, H.; Pan, D.; Huang, K. Roof Application of Bolter Miner Rapid Excavation Technology in Deep Underground Roadway in Inner Mongolia: A Case Study. *Sustainability* **2020**, *12*, 2588. [CrossRef]
3. Tang, B.; Yeboah, M.; Cheng, H.; Tang, Y.; Yao, Z.; Wang, C.; Rong, C.; Wang, Z.; Liu, Q. Numerical Study and Field Performance of Rockbolt Support Schemes in Tbm-excavated Coal Mine Roadways: A Case Study. *Tunn. Undergr. Space Technol.* **2021**, *115*, 104053. [CrossRef]
4. Chen, H.; Chen, H.; Xu, Y.; Zhang, D.; Ma, Y.; Mao, J. Research on Attitude Monitoring Method of Advanced Hydraulic Support Based on Multi-sensor Fusion. *Measurement* **2021**, *187*, 110341. [CrossRef]
5. Liu, H.; Jiang, Z.; Chen, W.; Chen, F.; Ma, F.; Li, D.; Liu, Z.; Gao, H. A Simulation Experimental Study on the Advance Support Mechanism of a Roadway Used with the Longwall Coal Mining Method. *Energies* **2022**, *15*, 1366. [CrossRef]
6. Zhang, K.; Li, Y.; Feng, L.; Meng, X.; Zhong, D.; Huang, L. Roof Deformation Characteristics and Experimental Verification of Advanced Coupling Support System Supporting Roadway. *Energy Sci. Eng.* **2022**, *10*, 2397–2419. [CrossRef]
7. Wang, F.; Duan, C.; Tu, S.; Liang, N.; Bai, Q. Hydraulic Support Crushed Mechanism for the Shallow Seam Mining Face Under the Roadway Pillars of Room Mining Goaf. *Int. J. Min. Sci. Technol.* **2017**, *27*, 853–860. [CrossRef]
8. Zhang, X.; Gong, P.; Wang, K.; Li, J.; Jiang, Y. Characteristic and Mechanism of Roof Fracture Ahead of the Face in an LTCC Panel When Passing an Abandoned Roadway: A Case Study from the Shenghua Coal Mine, China. *Rock Mech. Rock Eng.* **2019**, *52*, 2775–2788. [CrossRef]
9. Yang, X.; Huang, R.; Yang, G.; Wang, Y.; Cao, J.; Liu, J.; He, M. Validation Study of No-pillar Mining Method Without Advance Tunneling: A Case Study of a Mine in China. *Energy Sci. Eng.* **2021**, *9*, 1761–1772. [CrossRef]
10. Ge, X.; Xie, J.; Wang, X.; Liu, Y.; Shi, H. A Virtual Adjustment Method and Experimental Study of the Support Attitude of Hydraulic Support Groups in Propulsion State. *Measurement* **2020**, *158*, 107743. [CrossRef]
11. Feng, X.; Ding, Z.; Hu, Q.; Zhao, X.; Ali, M.; Banquando, J.T. Orthogonal Numerical Analysis of Deformation and Failure Characteristics of Deep Roadway in Coal Mines: A Case Study. *Minerals* **2022**, *12*, 185. [CrossRef]
12. Zeng, Q.; Li, Y.; Yang, Y. Dynamic Analysis of Hydraulic Support with Single Clearance. *Stroj. Vestn. J. Mech. Eng.* **2021**, *67*, 53–66. [CrossRef]
13. Liang, M.; Fang, X.; Li, S.; Wu, G.; Ma, M.; Zhang, Y. A Fiber Bragg Grating Tilt Sensor for Posture Monitoring of Hydraulic Supports in Coal Mine Working Face. *Measurement* **2019**, *138*, 305–313. [CrossRef]
14. Li, T.; Wang, J.; Zhang, K.; Zhang, C. Mechanical Analysis of the Structure of Longwall Mining Hydraulic Support. *Sci. Prog.* **2021**, *103*, 0036850420936479. [CrossRef]
15. Zhang, Y.; Zhang, H.; Gao, K.; Xu, W.; Zeng, Q. New Method and Experiment for Detecting Relative Position and Posture of the Hydraulic Support. *IEEE Access* **2019**, *7*, 181842–181854. [CrossRef]
16. Xie, Y.; Zeng, Q.; Jiang, K.; Meng, Z.; Li, Q.; Zhang, J. Investigation of Dynamic Behaviour of Four-leg Hydraulic Support under Double-Impact Load. *Stroj. Vestn. J. Mech. Eng.* **2022**, *68*, 385–394. [CrossRef]
17. Guo, C.; Mao, J. Anti-impact Load Characteristics of Two-stage Safety Valve for Hydraulic Support. *Ain Shams Eng. J.* **2022**, *13*, 101738. [CrossRef]
18. Hao, Y.; Wu, Y.; Chen, L.; Teng, Y. An Innovative Yielding Prop with High Stable Load Capacity and Long Shrinkage Distance in Coal Mine. *Mech. Adv. Mater. Struct.* **2019**, *26*, 1568–1579. [CrossRef]
19. Yu, Y.; Lu, J.; Pan, Y.; Zhao, X.; Chen, D. Research and Practice on Filling Technology of Fully Mechanized Coal Mining Face through Trend Abandoned Roadway. *Sustainability* **2021**, *13*, 9920. [CrossRef]
20. Juárez-Ferreras, R.; González-Nicieza, C.; Menéndez-Díaz, A.; Álvarez-Vigil, A.E.; Álvarez-Fernández, M.I. Forensic Analysis of Hydraulic Props in Longwall Workings. *Eng. Fail. Anal.* **2009**, *16*, 2357–2370. [CrossRef]
21. Xie, S.; Wu, X.; Chen, D.; Sun, Y.; Wang, E.; Wu, X.; Duan, X.; Jiang, Z.; Qi, P.; Shi, S. Failure Mechanism and Control Technology of Thick and Soft Coal Fully Mechanized Caving Roadway under Double Gobs in Close Coal Seams. *Shock Vib.* **2020**, *2020*, 8846014. [CrossRef]
22. Wang, X.; Yang, Z.; Feng, J.; Liu, H. Stress Analysis and Stability Analysis on Doubly-telescopic Prop of Hydraulic Support. *Eng. Fail. Anal.* **2013**, *3*, 274–282. [CrossRef]
23. Zhang, S.; Fan, G.; Chai, L.; Li, Q.; Chen, M.; Luo, T.; Ren, S. Disaster Control of Roof Falling in Deep Coal Mine Roadway Subjected to High Abutment Pressure. *Geofluids* **2021**, *2021*, 8875249. [CrossRef]
24. Wojciech, S. Modelling and Analysis of Damped Vibration in Hydraulic Cylinder. *Math. Comput. Model. Dyn. Syst.* **2014**, *21*, 23–37.
25. Yuan Ho Shan, R.; Su, X. Deformation Characteristics and Stability Control of a Gateroad in Fully Mechanized Mining with Large Mining Height. *Arab. J. Geosci.* **2018**, *11*, 767. [CrossRef]
26. Tan, Y.; Zhao, T.; Xiao, Y. Quantitative Prop Support Estimation and Remote Monitor Early Warning for Hard Roof Weighting at the Muchengjian Mine in China. *Can. Geotech. J.* **2010**, *47*, 947–954. [CrossRef]