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Review

Application of Gob-Side Entry Driving in Fully Mechanized Caving Mining: A Review of Theory and Technology

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Abstract: China has abundant coal resources, and the distribution of coal seams is complex. Thick coal seams account for more than 45% of all coal seams. Fully mechanized top coal caving mining has the advantages of large production, high efficiency, and low cost. In fully mechanized caving mining, especially in fully mechanized caving mining of extra-thick coal seams, the mining space is ample, the mine pressure is severe, and the roadway maintenance is complex. As a result, it is necessary to summarize and discuss the gob-side entry driving of fully mechanized caving in theory and technology, which will help to promote the further development of fully mechanized caving gob-side entry driving technology. First, in recent years, the research hotspots of gob-side entry driving have focused on the deformation mechanism and the control method of the roadway surrounding rock. Secondly, this paper discusses the theoretical models of the "triangle-block" and "beam" for the activity law of the overlying strata in gob-side entry driving, including the lateral breaking "large structure" model, compound key triangle block structure model in the middle and low position, the high and low right angle key block stability mechanics model, elastic foundation beam model, low-level combined cantilever beam + high-level multilayer masonry beam structure model, and the vertical triangular slip zone structure model. It introduces the "internal and external stress field theory" and the "stress limit equilibrium zone model". Thirdly, it summarizes several numerical simulation analysis methods in different conditions or research focuses and selects appropriate constitutive models and simulation software. Finally, it introduces surrounding rock control technology, including two ribs, the roof, and under challenging conditions. It provides a method reference for support in similar projects.

Keywords: fully mechanized top coal caving mining; gob-side entry driving; triangle-block structure; beam structure; cable truss; support

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1. Introduction

The recoverable reserves of thick coal seams in China account for about 45% of the total reserves of production mines [1]. The thick coal seam mining method has always been an important research topic in the coal industry [2–4]. The most common method of mining thick coal seams in China is fully mechanized top coal caving. In mining, most of the working face roadways will leave a certain width of a section coal pillar to protect the roadway, which is responsible for supporting the overlying strata and isolating the goaf water and harmful gas [5–8]. The width of the coal pillar increases as the mining intensity and geological conditions become more complex, resulting in a significant loss of coal resources [9,10]. Nonpillar or narrow coal pillar mining methods have been proposed to improve the recovery rate of coal resources. Gob-side entry driving is an important method of nonpillar mining in mining roadways [11]. Maintaining narrow coal pillars not only puts the roadway in the stress reduction zone [12,13] but also reduces coal pillar loss and improves the resource recovery rate. As a result, gob-side entry driving mining has been extensively used in thick coal seam mining.

Scholars from both home and abroad have researched the related problems of gob-side entry driving [14–16]. In terms of the activity law of the overlying strata [17] in gob-side entry driving, they put forward various theories based on the mechanical model of the "triangle-block" [18–21] and "beam". In fully mechanized caving section roadway surrounding rock control theory, they put forward the "internal and external stress field theory" and the "stress limit equilibrium zone model". The proposal of these theoretical models has extensively promoted the development and application of gob-side entry driving in fully mechanized caving mining. Based on these theories, we can make correct guidance for production practices. However, the current theory has limitations, and theoretical research must be strengthened. The numerical simulation [22] of gob-side entry driving in fully mechanized caving found that the strain-softening constitutive model is mainly used to study the reasonable width of the coal pillar [23–26]. Considering the compaction effect of gangue in goaf, the double-yield model is often used to study its influence on stress redistribution [27]. Numerical simulation is an indispensable technical means in mining engineering. Although the numerical simulation results sometimes do not reflect the actual situation well, they can also provide some reference. To control the surrounding rock of gob-side entry driving in fully mechanized caving, with the development of coal mine support technology [28–30], this method gradually changed from an initial shotcrete wall [31,32] and shed support [33] to a high prestressed anchor bolt and anchor cable support. In addition, for the asymmetric deformation problem of gob-side entry, they proposed an asymmetric cable truss [34–37] and step-bundled anchor cable [31,32] support way and achieved an excellent supporting effect. In order to ensure efficient and safe production, roadway surrounding rock control has always been an important research topic in the mining field. The mine pressure is severe in a fully mechanized caving roadway, and roadway maintenance is complex. Therefore, a safe and efficient support method is needed.

Gob-side entry driving is usually arranged at the edge of the goaf of the previous working face. After the overlying rock in the goaf has collapsed and become stable, retaining the smaller width coal pillar (generally 5–8 m) plays an isolation role. It drives the roadway along the edge of the goaf [38]. The popularization and application of gob-side entry driving mining are conducive to promoting the development of mining roadway support theory, effectively improving the recovery rate of coal resources and having obvious social and economic benefits. As shown in Figure 1, according to the mining geological conditions, gob-side entry driving in fully mechanized caving mining is mainly applied to incline extra-thick coal seam caving mining, three soft coal seam caving mining, large mining height caving mining, thick and hard basic roof caving mining, island working face caving mining, deep well caving mining, and large section caving mining [39–41].

With theoretical research and mine equipment development, gob-side entry driving has gradually become an essential means in fully mechanized caving mining [42]. Therefore, the coal recovery rate increases, the surrounding rock of the roadway is effectively controlled, and the incidence of accident disasters is reduced, promoting high-quality and efficient coal mining. The research hotspot map was obtained by analyzing the research status of gob-side entry driving in fully mechanized caving mining in recent years, as shown in Figure 2.

It can be seen from Figure 2 that the research hotspots of gob-side entry driving in fully mechanized caving mainly focus on the following five aspects: ① stability of the surrounding rock; ② deformation mechanism of the surrounding rock; ③ reasonable roadway positions and the coal pillar width; ④ numerical simulation analysis of gob-side entry driving; and ⑤ roadway surrounding rock control technology.

By searching the keywords "gob-side entry driving" in CNKI, more than 170 related pieces of literature in recent years were obtained. Figure 3 depicts the subject words of these research papers: gob-side entry driving, extra-thick coal seam mining, fully mechanized top coal caving mining, reasonable width of coal pillar, surrounding rock control [43], large mining height mining, research and application, large section, numerical simulation, and island working face. Among them, research on the appropriate section coal pillar width [44,45] of gob-side entry driving in fully mechanized caving is a hot topic, accounting for 25%.

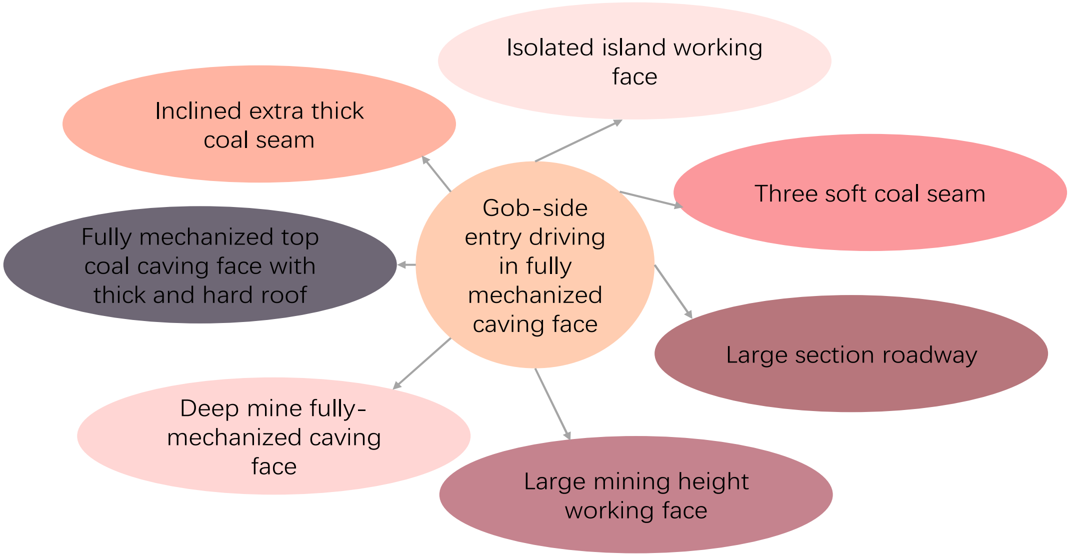


Figure 1. Some research directions of gob-side entry driving in fully mechanized caving mining.

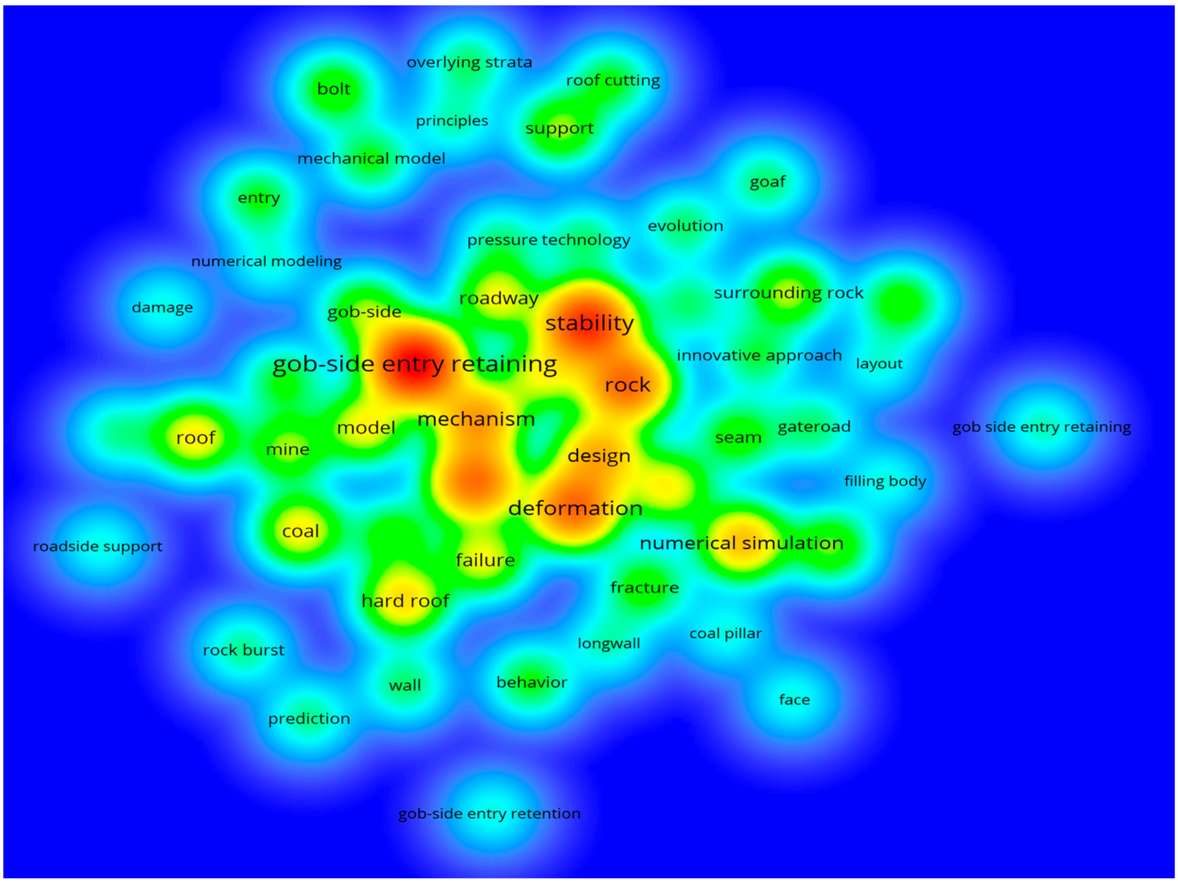


Figure 2. Research hotspot map of gob-side entry driving in fully mechanized caving.

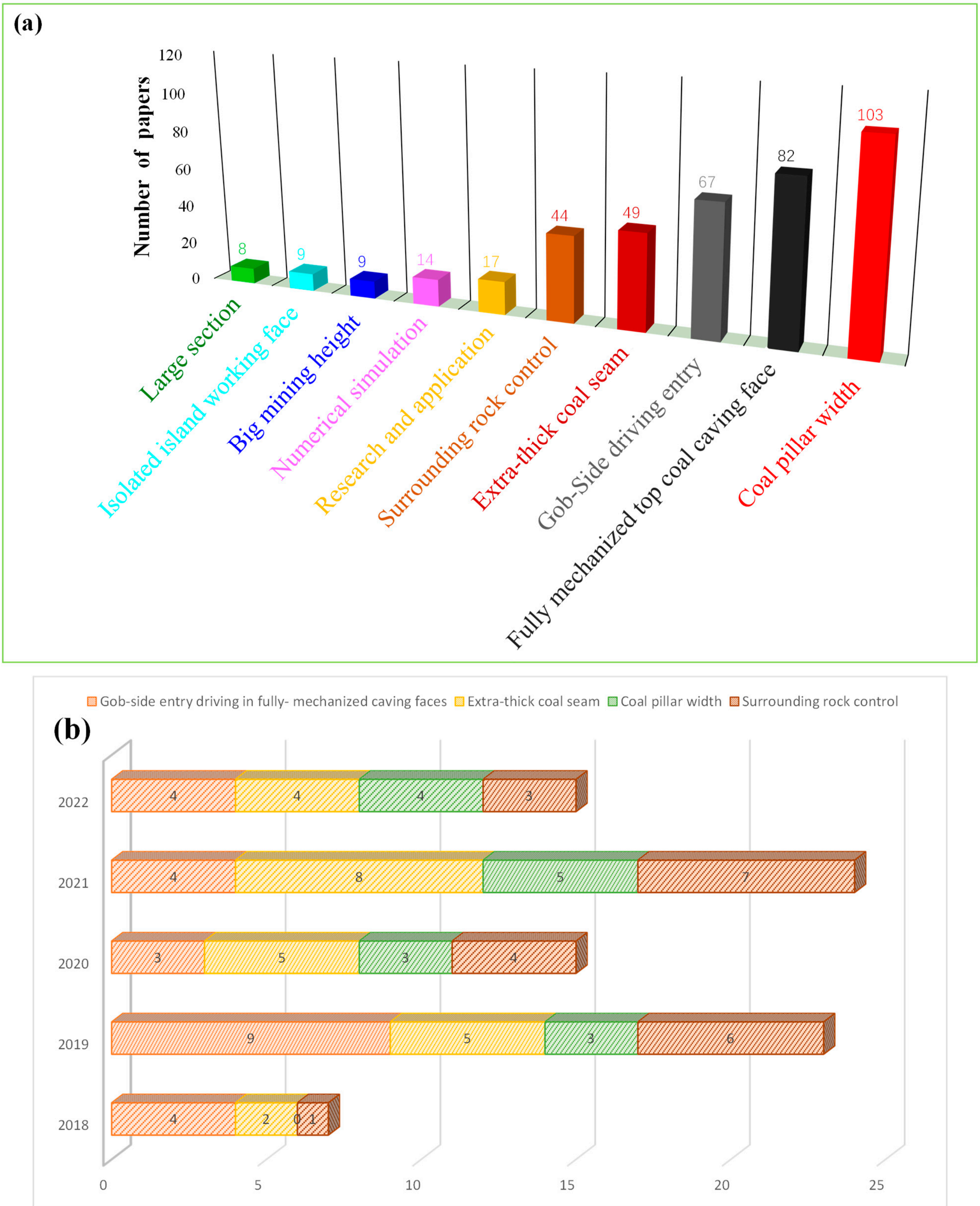


Figure 3. Research on gob-side entry driving technology in fully mechanized caving mining in China: (**a**) 10 research hotspots and (**b**) research trends in recent 5 years.

In this paper, the technology of gob-side entry driving with fully mechanized caving in recent years will be summarized in an all-around way. The related theories, numerical simulation constitutive models, research methods, and surrounding rock control technology will be systematically expounded. With proposals such as "carbon neutralization" and "carbon peak", coal mining is increasingly advocating for the development of safe mining technology with a high recovery rate. Fully mechanized caving along the goaf is widely used to realize a coal pillar reduction or no coal pillar. Therefore, this paper takes this as the research object. We analyze the application status and development prospects of gob-side entry driving in fully mechanized caving. When some experts or scholars need to preliminarily understand the relevant knowledge on gob-side entry driving, this paper can provide some guidance.

2. Research on the Theoretical Model of Gob-Side Entry Driving in Fully Mechanized Caving Mining

Fully mechanized top coal caving mining is a necessary technical means for high yield and high efficiency of coal mines in China. In terms of the movement law of the overlying strata in gob-side entry driving, scholars have constructed a mechanical model of the "triangle-block" and "beam" of the overlying rock, including the lateral breaking "large structure" model, compound key triangle block structure model in the middle and low position, the "high and low right angle key block stability mechanics model", elastic foundation beam model, low-level combined cantilever beam + high-level multilayer masonry beam structure model, and the vertical triangular slip zone structure model. In fully mechanized caving section roadway surrounding rock control theory, they put forward the "internal and external stress field theory" and the "stress limit equilibrium zone model".

2.1. Activity Law of Overlying Strata in Gob-Side Entry Driving

2.1.1. Mechanical Model of the "Triangle-Block"

(1) The lateral breaking "large structure" model

When the working face is left with narrow coal pillars, mining will significantly affect the surrounding rock, and the movement of the overlying strata will be violent, which will cause potential safety hazards. By analyzing the characteristics of the surrounding rock, scholars put forward the stability control principle of the "large structure" of the lateral breaking of the overlying strata in the adjacent goaf and the "small structure" of the overlying roof of the roadway surrounding rock. They established the large structure model of the overlying rock mass of the roadway driving along the goaf, as shown in Figure 4 [46]. By analyzing the stability of the triangular arc block of a basic roof, as shown in Figure 5, scholars proposed a surrounding rock control mechanism. Among them, F_Z is the resultant force of the self-weight of key block B, F_R is the resultant force of the self-weight of the upper weak overburden rock, the vertical force and horizontal force of rock block A to key block B are R_A and F_A, respectively, and the vertical shear force and horizontal thrust of structural block C to key block B are R_B and F_B, respectively, the supporting force of the gangue, end coal, and lateral coal in the goaf to key block B are F_G, F_{SM}, and F_M.

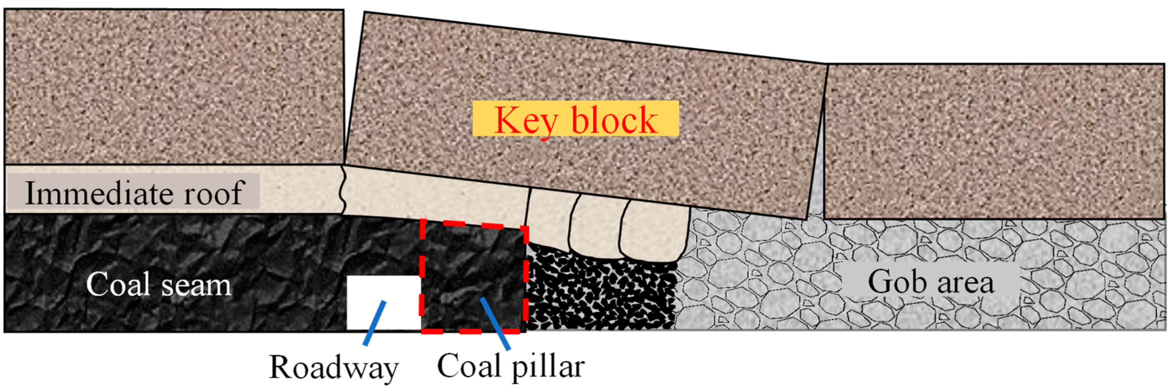


Figure 4. The lateral breaking structure model [46].

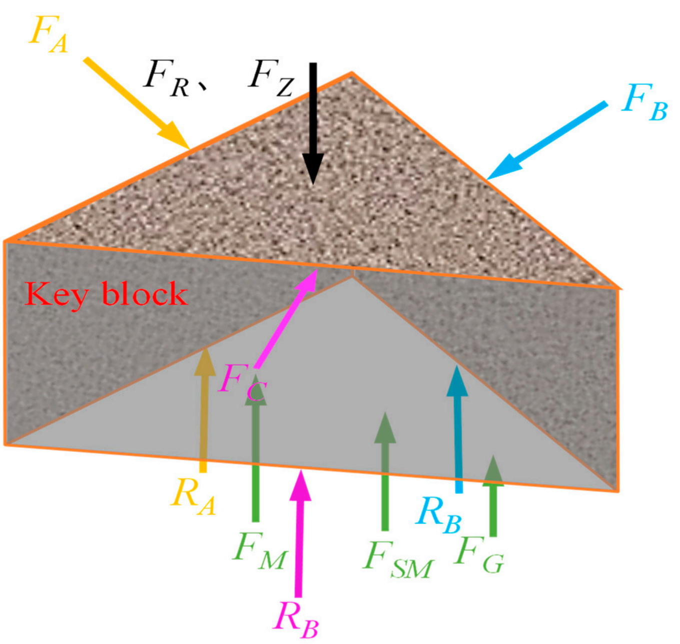


Figure 5. Mechanical analysis of the lateral breaking "large structure".

(2) Compound key triangle block structure model in the middle and low position

The construction of a mechanical model of a middle and low composite key triangular plate structure with synchronous and asynchronous migration of a basic roof (low position) at the end of the adjacent goaf of a fully mechanized caving face and the adjacent key hard rock layer (middle position) is shown in Figures 6 and 7. The stability characteristics and engineering disaster conditions of the key triangular plate structure in three-time states (before the formation of the section coal lane, after the formation of the section coal lane, and at the time of mining) were explored. The fracture position of the main roof of fully mechanized caving and its influence were obtained [47]. The same symbols in Figures 5 and 7 also have the same meaning. In addition, F'_Z is the resultant force of the self-weight of key block B (mesoposition), and F'_R is the resultant force of the self-weight of the upper weak overburden (mesoposition). The movement of weak rock strata above key block B separates from the hard rock strata above it and loses the transmission of force, namely, $F_X = 0$.

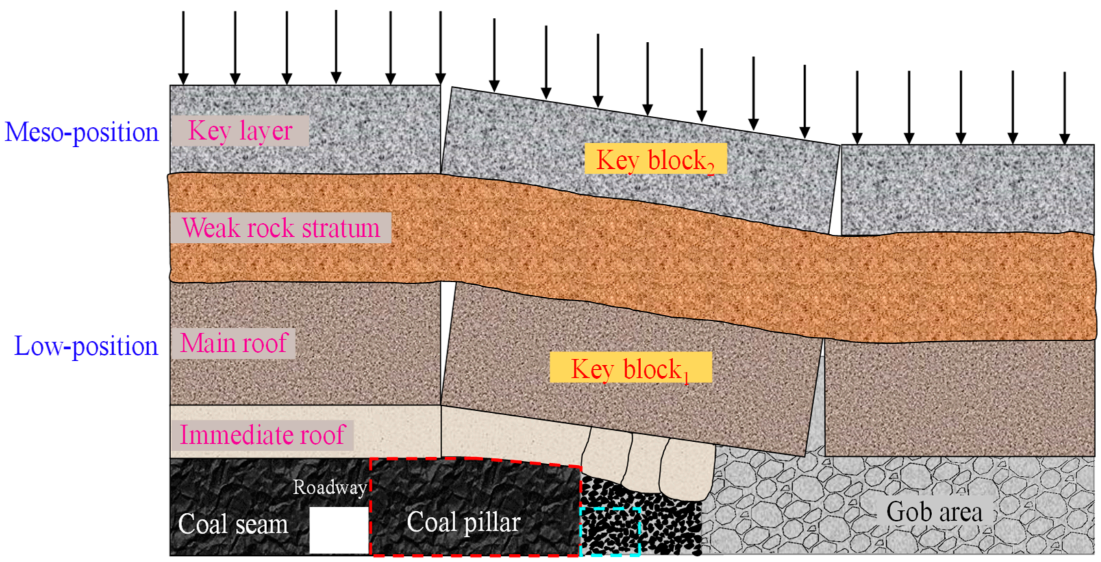


Figure 6. Compound triangle block structure model [47].

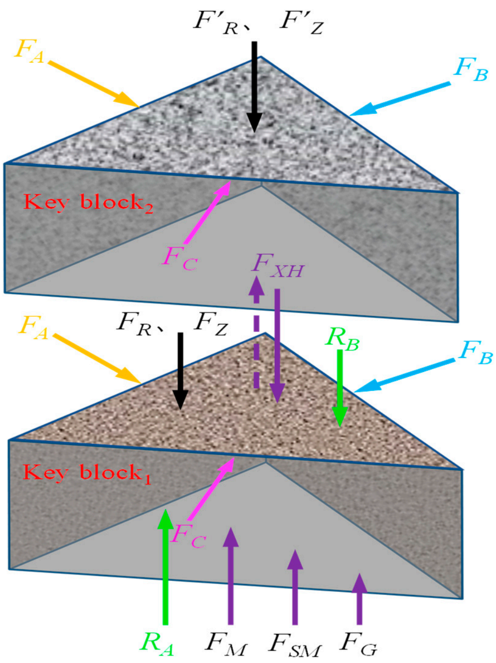


Figure 7. Mechanical analysis of the key triangular plate structure [47].

(3) The high and low right angle key block stability mechanics model

In fully mechanized caving mining of extra-thick coal seam with a hard and thick main roof, the mining space is large, and the strength is high, which causes the overlying strata to fracture, move, and collapse, and the influence is vast. Therefore, the low-key and high-key strata play a key role in the stability of the surrounding rock of the gob-side entry. Based on the theory of internal and external stress field and limit equilibrium theory, as shown in Figures 8 and 9, scholars have deduced a mechanical model for the stability of high and low right-angle key blocks with periodic breaking [48] and analyzed the joint stability of high and low key blocks.

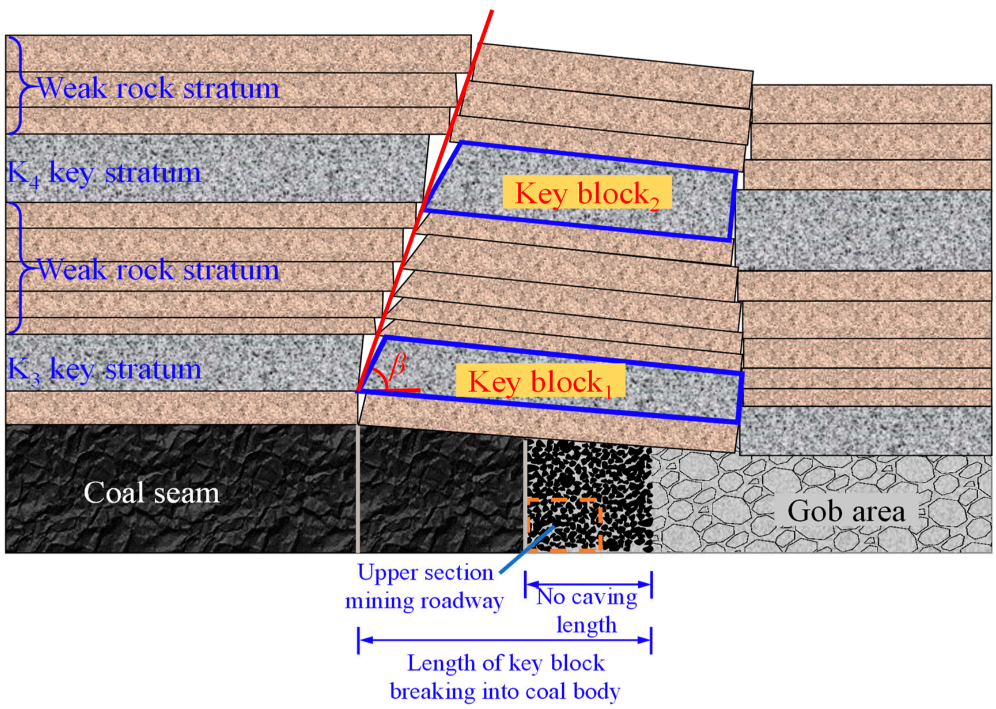


Figure 8. Fracture morphology of key blocks [48].

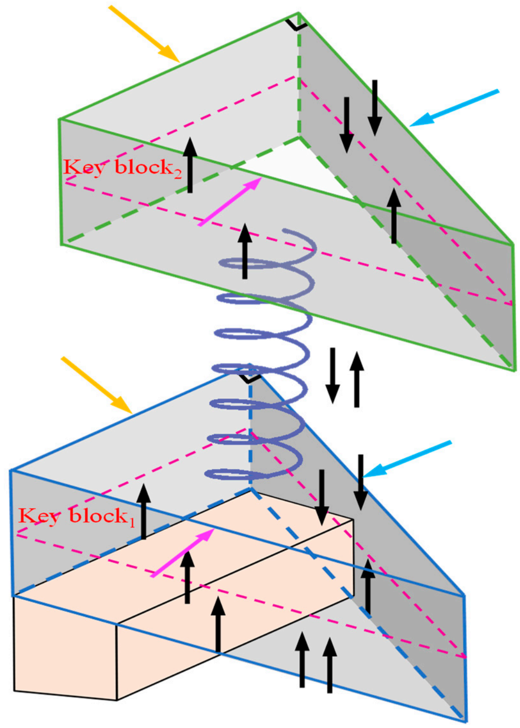


Figure 9. Mechanical analysis of high and low right angle key blocks [48].

2.1.2. Mechanical Model of the "Beam"

(1) Elastic foundation beam model

This model was based on the theory of masonry beams with lateral roof fracture, considering the deformation characteristics of coal seam and immediate roof. Scholars have established the basic roof elastic foundation beam model, as shown in Figure 10. They deduced the expressions of the lateral roof bending moment and displacement and then obtained the basic roof breaking position; the influence of the main roof, immediate roof, and coal seam thickness and elastic modulus on the lateral fracture position of the roof was explored [49]. Figure 11 shows the overburdened structure after the basic roof is broken.

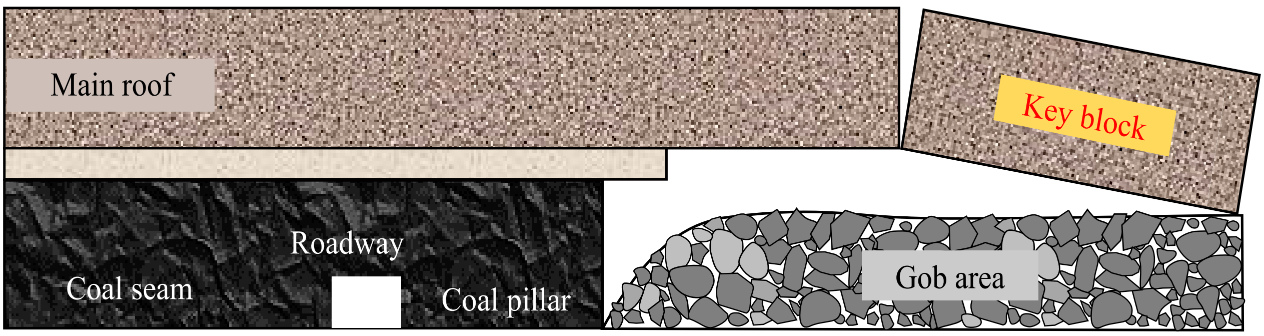


Figure 10. Structural model of elastic foundation beam [49].

(2) Low-level combined cantilever beam + high-level multilayer masonry beam structure model

The mining space formed by the mining of the fully mechanized caving face in the extra thick coal seam is large, the roof breaking and migration range are wide, and the development height of the overburdened caving zone and the fracture zone is significantly increased. When there are multiple layers of hard rock strata in the roof, the overlying hard key stratum breaks not only one layer but multiple layers. Therefore, for the mining of extra-thick coal seam with a hard roof, scholars have proposed a lateral overburden structure model of "low-level combined cantilever beam + high-level multi-layer masonry beam" in the roadway of extra-thick coal seam with a hard roof, as shown in Figure 12 [50].

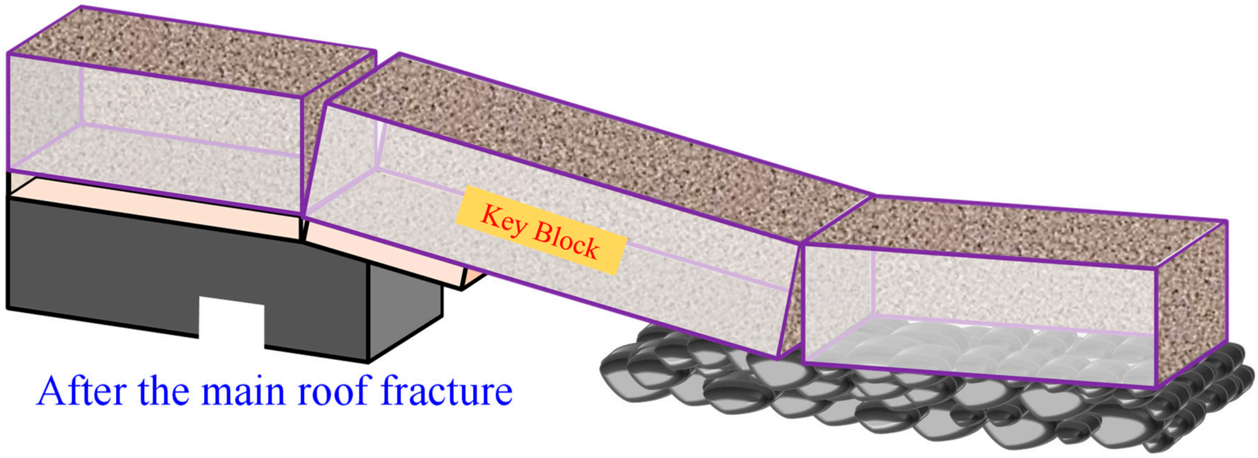


Figure 11. Overburden rock structure.

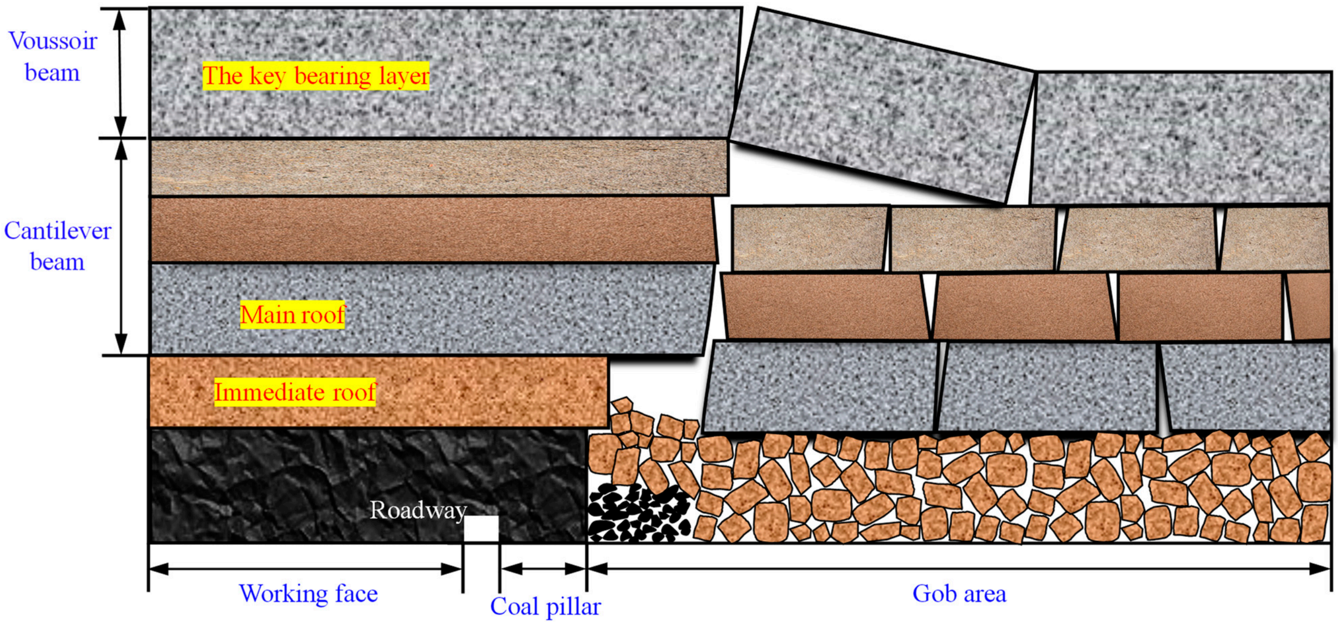


Figure 12. Low-level combined cantilever beam + high-level multilayer masonry beam structure model [50].

(3) The vertical triangular slip zone structure model

Scholars took a fully mechanized caving face with a large mining height in an extra-thick coal seam as their research object and analyzed the activity range, fracture field distribution, motion characteristics, and structural characteristics of the overlying strata at the end of the working face with a large mining height in the extra-thick coal seam. It was proposed that there is a stable stress reduction zone with a triangular slip zone structure at the end of the goaf. This is conducive to the layout of gob-side entry driving with a small coal pillar and the maintenance of a small coal pillar roadway. According to the movement characteristics of the overlying strata in the goaf and the time–space relationship, the reasonable position and time of the small coal pillar driving along the goaf were determined, as shown in Figure 13 [51].

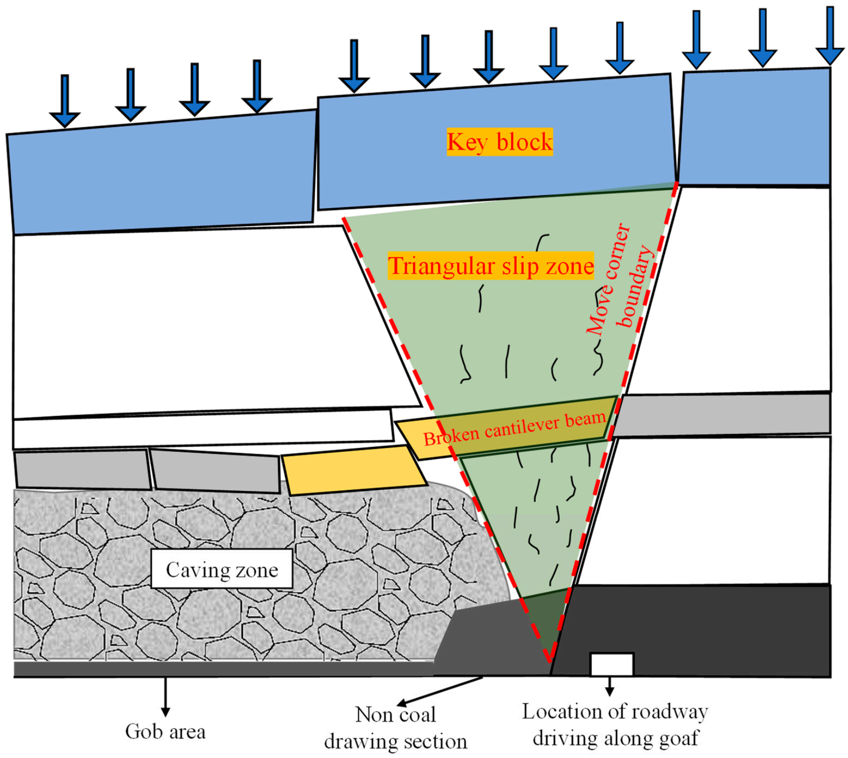


Figure 13. The vertical triangular slip zone structure model [51].

2.2. Surrounding Rock Control of Fully Mechanized Caving Section Roadway

2.2.1. The "Internal and External Stress Field Theory"

Scholars have established the structural mechanics model of gob-side entry driving by the theoretical analysis method. They established the expression of "internal stress field" width and determined the reasonable position of gob-side entry driving and the reasonable width of the coal pillar. They predicted the deformation of the surrounding rock of gob-side entry driving, as shown in Figure 14 [52]. The movement law and deformation failure characteristics of the surrounding rock of the roadway and the curved triangular block of the end basic roof in different stages were studied. The overall mechanical environment of the fully mechanized caving along the goaf was analyzed, and stability control theory was preliminarily formed. In Figures 15–17 [53], scholars also established a mechanical model of the roadway surrounding rock structure. The relationship between the key block's rotation angle and the coal pillar's overlying load was obtained, and the coal pillar's width was calculated to determine the fracture position of the basic roof. In Figure 14, the interval calibrated by S_1 is called the "internal stress field", and the interval calibrated by S_2 is called the "external stress field". σ_y is the lateral support pressure; K is the stress concentration factor; and γ is the average bulk density of the overlying strata. Moreover, H is the buried depth of the roadway.

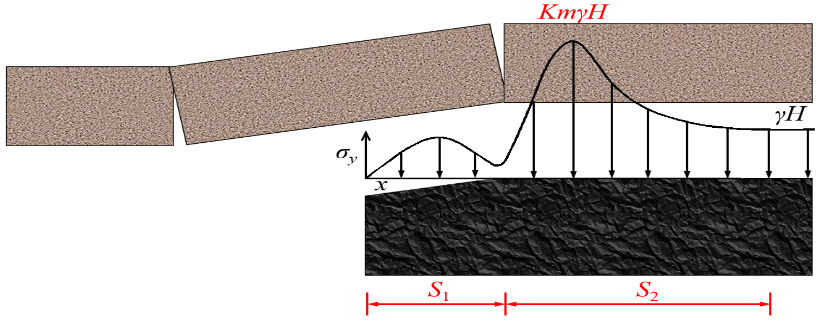


Figure 14. Structural mechanics model of gob-side entry driving [52].

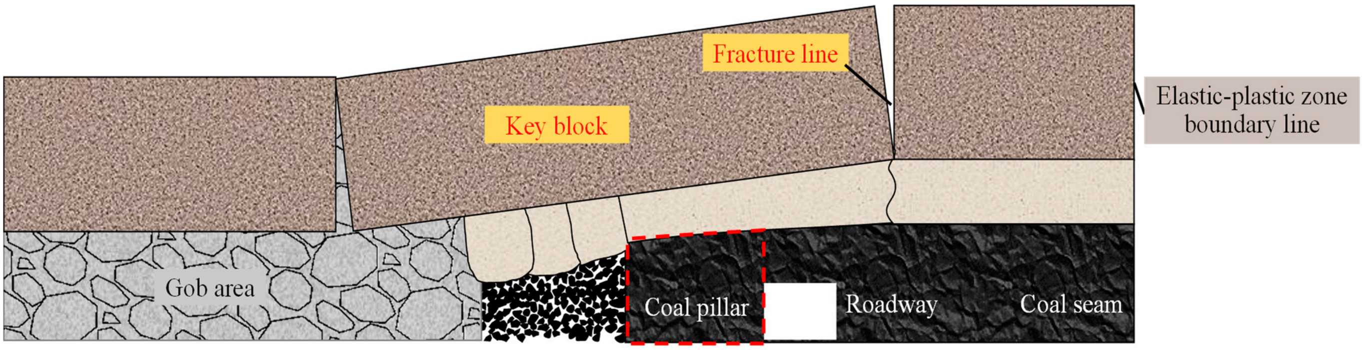


Figure 15. Structure model with main roof fracture line above the solid coal [53].

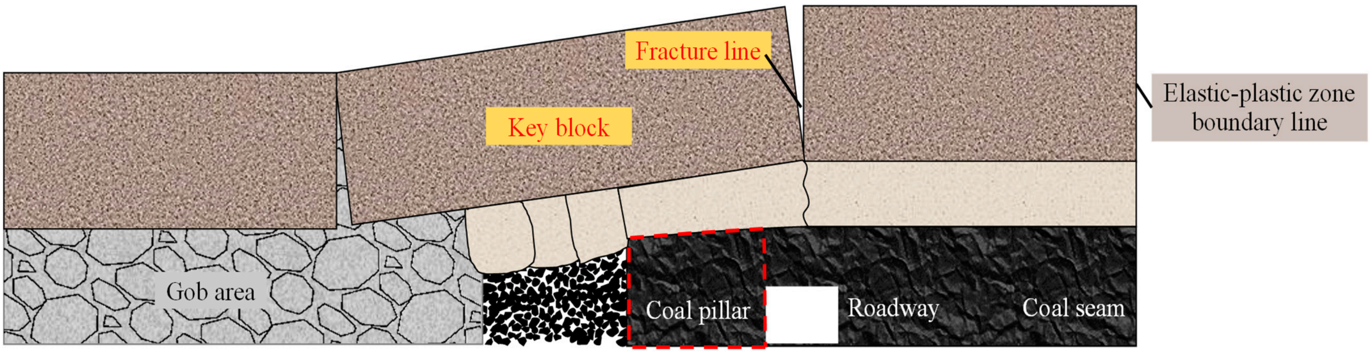


Figure 16. Structure model with main roof fracture line above the roadway [53].

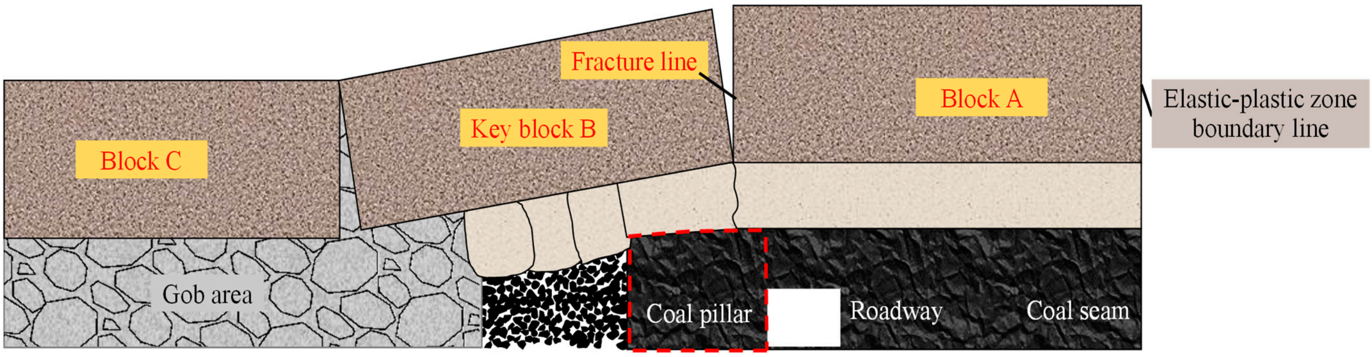


Figure 17. Structure model with main roof fracture line above the coal pillar [53].

2.2.2. The "Stress Limit Equilibrium Zone Model"

In Figures 18 and 19, based on the stress characteristics of the surrounding rock of gob-side entry driving in deep-well fully mechanized caving, considering the strength-softening characteristics of coal and rock mass at the interface between the roadway side and roof and floor, scholars have established the mechanical analysis model of two ribs and deduced the theoretical calculation of the limit equilibrium zone width and the coal stress displacement of two ribs [54]. Based on the distribution characteristics of the inclined abutment pressure of the coal body on the goaf side and the limit equilibrium theory of a coal pillar in roadway protection, the analytical expressions of the upper and lower limits of a reasonable width of a narrow coal pillar in roadway protection were determined [55]. Based on analyzing the stress environment of gob-side entry driving, the principle of damage mechanics was used to analyze the abutment pressure distribution of the solid coal side of gob-side entry driving under the given deformation, and the relationship between the abutment pressure distribution and parameters such as the coal rock thickness and elastic modulus was discussed. It is of great significance to the upkeep of gob-side entry as well as the study of the floor heave mechanism and control [56]. In Figure 18, the shear stress at the interface between the coal seam and the roof and floor is τ_{xy}, the vertical pressure is σ_y, the horizontal stress inside the coal rock mass is σ_x, and the roadway rib support resistance is f_i. In Figure 19, f_s is the support resistance of the general goaf side, f_z is the support resistance of the roadway side, and the peak stress in the limit equilibrium zone of the coal pillar side should be σ_{ym}.

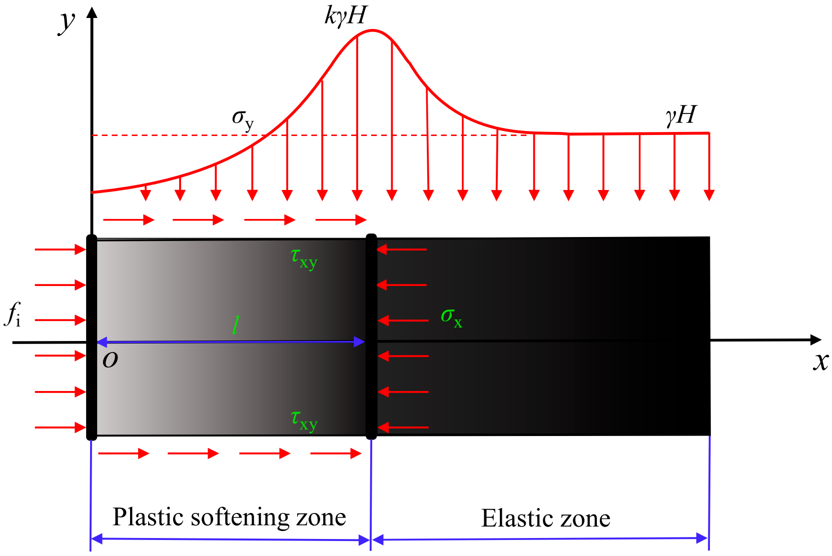


Figure 18. The mechanical model of solid coal rib [54].

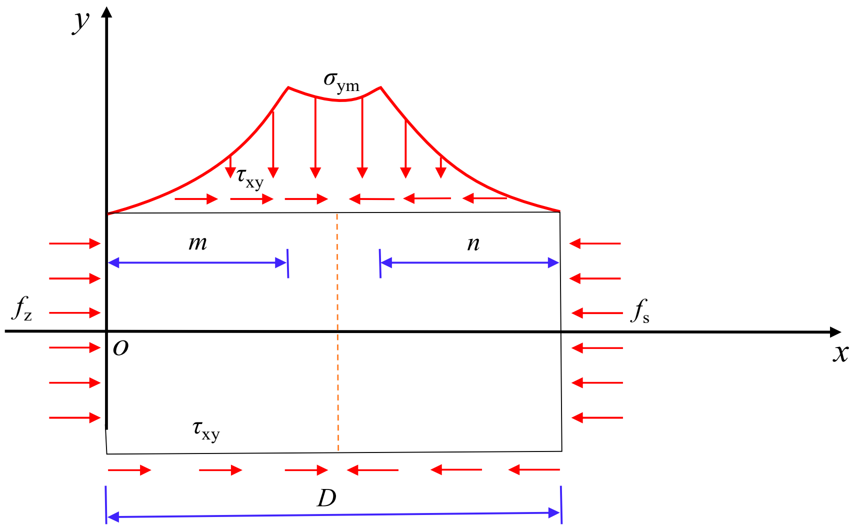


Figure 19. The mechanical model of coal pillar rib [54].

Among the above many theoretical models, the rock beam model belongs to a relatively simplified model, and the triangular block structure is a theoretical model that is more recognized by scholars at present. It is also more often used in the related research of gob-side entry driving.

3. Numerical Analysis Method of Gob-Side Entry Driving in Fully Mechanized Caving Mining

Numerical simulation is an indispensable technical means in mining engineering. At present, the most commonly used numerical analysis methods are the finite element method, boundary element method, finite difference method, weighted residual method, discrete element method, rigid body element method, discontinuous deformation analysis

(DDA) method, manifold element method [57], etc. In the study of fully mechanized caving gob-side entry driving engineering problems, scholars often use FLAC^{3D}, UDEC, PFC, and other numerical software according to different working conditions and select the appropriate software analysis [58–61]. As shown in Figure 20, it shows the constitutive model used in FLAC^{3D}.

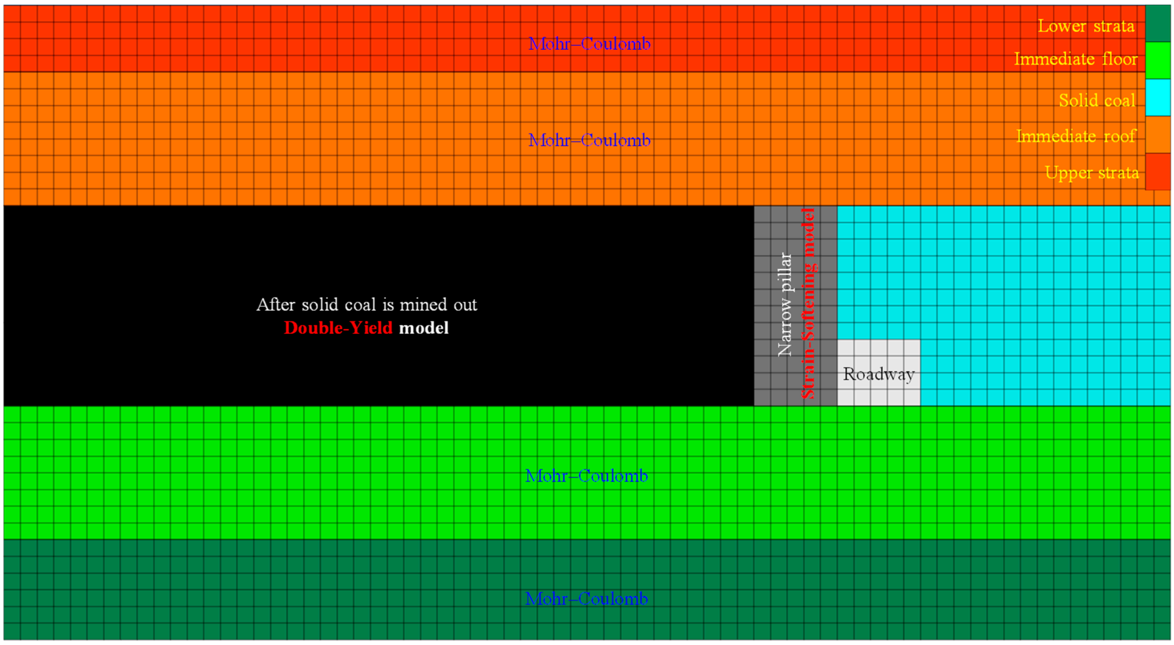


Figure 20. Constitutive model of FLAC^{3D} used gob-side entry driving in fully mechanized caving.

3.1. Constitutive Model of FLAC^{3D}

3.1.1. Strain-Softening Model of Yielding Coal Pillar

In studying the surrounding rock control of gob-side entry driving in fully mechanized caving, many scholars mostly choose the strain-softening constitutive model when studying reasonable coal pillar width. Compared with the Mohr–Coulomb constitutive model, it can more truly reflect the yield of the small coal pillar, especially when retaining a small coal pillar. It can also provide an accurate and reliable basis for formulating a sensible coal pillar width and support [23–26]. The strain-softening model reflects the real failure properties of coal pillars as follows: the elastic stage is consistent with the Mohr–Coulomb model. After entering the plasticity, the cohesion and friction will gradually decrease with the plastic strain [30,62,63].

FLAC3D finite difference software has a strain-softening constitutive model [60]. Scholars have established a standard specimen model for a uniaxial compression 1:1 simulation and carried out the corresponding parameter iterative inversion through indoor test and numerical simulation then fitted the standard specimen parameters for numerical simulation [64–66].

3.1.2. Double-Yield Model of Goaf

Due to the compaction of gangue in the goaf, the stress state of the surrounding rock in the gob-side entry will be affected [67]. Therefore, the double-yield model can well-simulate the influence of gangue on stress redistribution [27]. In the gob-side entry driving process, the coal pillar's bearing capacity needs to be considered, and the influence on the goaf cannot be ignored [68–73]. In the numerical simulation, the "cap pressure" is the parameter that mainly determines the compaction characteristics of the goaf material in the simulation, which is controlled by Table [74,75]. According to the classical theoretical formula of Salamon, the corresponding parameter inversion is carried out by establishing a 1 m × 1 m × 1 m model in the numerical simulation so that the parameters can precisely reflect the actual condition [76,77]. The specific parameter inversion process in the numerical model is shown in Figure 21.

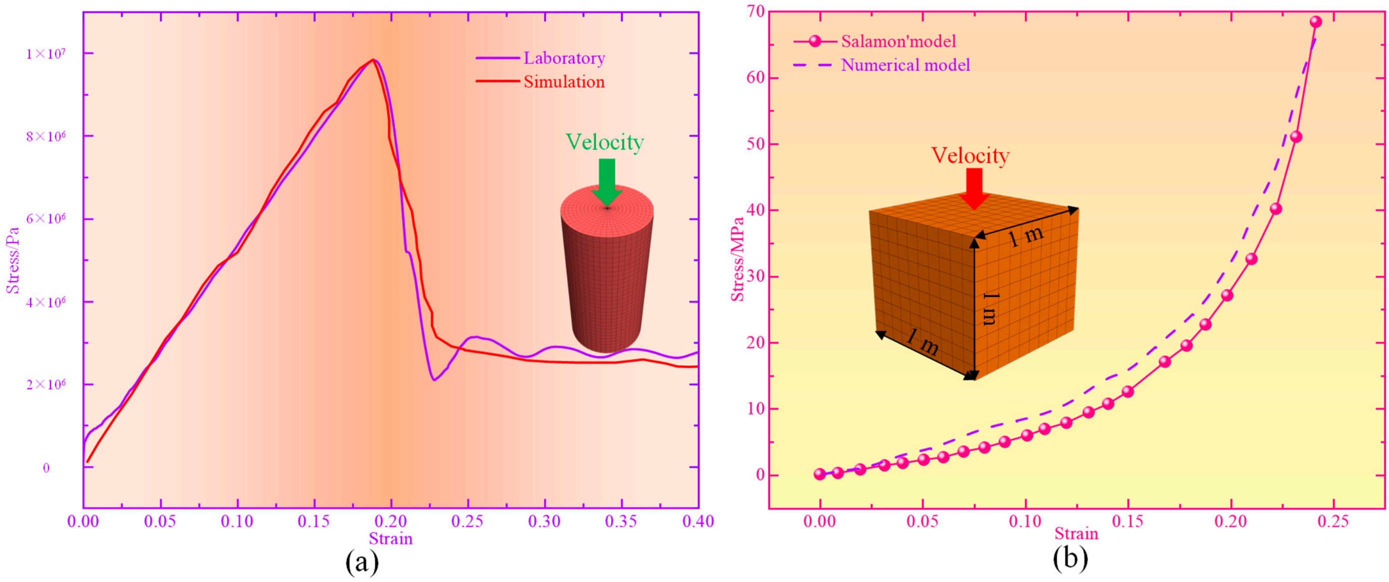


Figure 21. Inversion fitting process of constitutive model parameters in numerical simulation: (**a**) strain-softening model and (**b**) double-yield model.

3.2. UDEC Simulation of Coal Pillar Fracture

Through the UDEC (a discrete element software), many scholars can intuitively see the fracture development and damage degree in the coal pillar of gob-side entry driving [78–81]. By analyzing the crack propagation morphology and plastic state in the coal pillar, they can guide the reasonable setting position of the gob-side entry and coal pillar width to minimize the influence of the coal pillar on the stability of the roadway [82–84]. As shown in Figure 22, it indicates the development state of coal pillar cracks in gob-side entry driving.

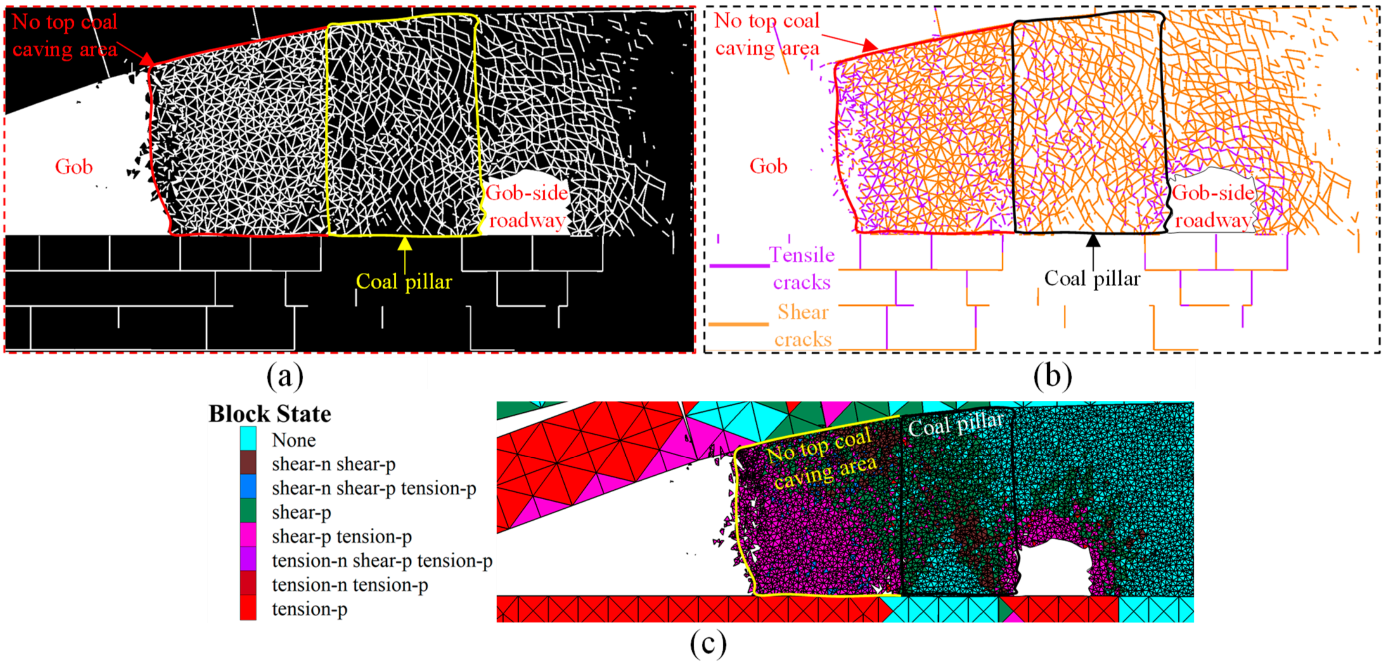


Figure 22. Development state of coal pillar fracture of gob-side entry driving in fully mechanized caving: (**a**) fracture pattern, (**b**) cracks, and (**c**) state.

3.3. Other Numerical Analysis Methods

Many scholars have carried out uniaxial and triaxial compression simulation tests by sampling coal on-site and combining discrete element software PFC^{2D}/PFC^{3D} to explore the crack propagation law of coal specimens under the condition of prefabricated cracks [85–87] to guide the setting of coal pillars in gob-side entry driving to ensure the optimal stress field environment of roadway surrounding rock. Some scholars have studied the dynamic, progressive failure process of coal rock samples through CDEM to analyze the influence of cracks on the stability of coal rock columns [88,89].

4. Surrounding Rock Control Technology of Gob-Side Entry Driving in Fully Mechanized Caving Mining

The structural characteristics of overburdened roadway rock differ in different mining stages of gob-side entry driving, which has a significant impact on the surrounding rock support [90]. It is essential for the stability of the surrounding rock to optimize the support parameters according to the structural characteristics of the overlying rock [91]. Scholars have put forward various supporting technologies for roadway driving along the goaf. This paper will introduce the surrounding rock control technology from three aspects: two ribs, the roof, and other complex conditions.

4.1. Two-Rib Support of the Roadway

4.1.1. Support of Coal Pillar Rib

In gob-side entry of fully mechanized caving, the coal pillar rib usually adopts general support forms, such as a bolt + ladder beam of steel (W, JW steel strip) + mesh and anchor cable support. However, with the progress of fully mechanized caving mining, the fracture development of the coal pillar is obvious, and the stress concentration at the end of fracture is obvious, which leads to the weakening of the bearing capacity and an antideformation and failure ability of the coal pillar [92,93]. The linkage between the coal pillar and top coal is large. The failure of the coal pillar reduces the stability of the top coal, increasing the deformation and pressure of the roadway and increasing the difficulty of support. Using an ordinary bolt and cable support on the coal pillar's rib to maintain stability is challenging. Roadside support can assist the coal pillar in bearing roof pressure and improve the bearing capacity of the coal pillar.

The roadside support of gob-side entry driving is mainly divided into concrete wall support on the side of the coal pillar roadway and filling support on the side of the coal pillar goaf, as shown in Figure 23. The pouring concrete wall support on the side of the coal pillar roadway refers to establishing a certain width of the reinforced concrete wall in the roadway. The supporting wall is connected with the roof, floor, and the coal pillar rib through the preset high-strength bolt. Therefore, the reinforced concrete wall and the surrounding rock are coordinated [31,32]. The filling support of the goaf side of the coal pillar refers to the injection of foam, fly ash material, high water material, paste material, or cement slurry near the goaf side of the coal pillar. It can replace part of the falling gangue or directly fill it, thereby reducing the roof activity space [94,95].

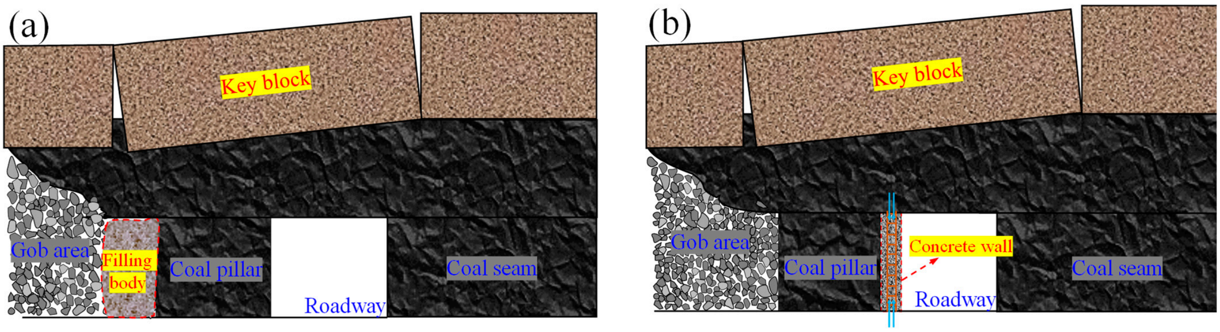


Figure 23. *Cont.*

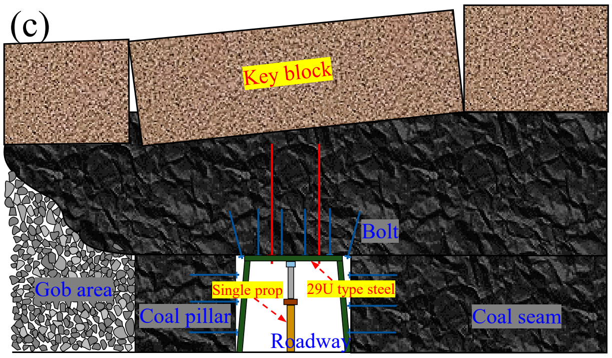


Figure 23. Support diagram of coal pillar rib: (**a**) filling support on the side of the goaf, (**b**) concrete wall support on the side of the roadway, and (**c**) general bolt and anchor cable support. (**a**,**b**) [31,32] and (**c**) [94,95].

4.1.2. Support of Virgin Coal Rib

The degree of mine pressure on the virgin coal rib is small, and the damage to the surrounding rock of the roadway is also tiny. As a result, the support method is simple. Bolt + ladder beam of steel (W, JW steel strip) + mesh is often used, and sometimes a single anchor cable is also used for reinforcement support.

4.2. Roof Support of Gob-Side Entry Driving

For a long time, scholars have conducted much research on the problem of roof control in gob-side entry driving. The roof is usually controlled with a combination of various support methods, among which, the most commonly used is bolt support [44]. The arrangement of bolt support in various fully mechanized caving roadways is the same, so this paper focuses on roof control technology with an anchor cable as the core.

4.2.1. Single Anchor Cable Support or Anchor Cable + Steel Strip Support

When the coal seam thickness is less than six m, two or three independent single anchor cables are arranged on the roof for support, as shown in Figure 24a,b, and the anchor cable can be anchored to the stable rock stratum. W steel strips are also commonly used to connect the anchor cables, as shown in Figure 24c,d.

4.2.2. Anchor Cable Truss Support

The anchor cable truss comprises a long anchor cable and a special connecting lock device [96]. Figure 24e,f represents symmetric and asymmetric layouts, respectively. The special connecting lock device connecting the long anchor cable is shown in Figure 24g.

Figure 24h indicates its control principle [97,98]: The cable truss system gradually locks during roof rock deformation, increasing the compression value of shallow surrounding rock and preventing excessive deformation of roadway surrounding rock; the anchor cable truss has a long length and solid shear resistance. It crosses the greatest shear stress area at the coal pillar–roof junction obliquely, enhancing the surrounding rock's shear resistance and maintaining its stability in the coal pillar's corner area.

4.2.3. Cable Beam Truss Support

The cable beam truss structure comprises a long anchor cable, channel steel support beam, steel support beam, and lock. The single anchor cable is first connected with a high-strength steel support beam, and the anchor cable near the side of the coal pillar is connected with a channel steel support beam for a secondary connection. The support structure is arranged near the side of the coal pillar rib, as shown in Figure 24i,j. Figure 24k is the on-site support diagram, and Figure 24l is the supporting principle diagram.

The control principle is as follows: After applying a high pretightening force, the anchor cable, steel (channel steel) support beam, and coal–rock mass form an inverted trapezoidal bearing structure. When subjected to unbalanced abutment pressure, the inverted trapezoidal structure jams the two corners. The greater the load, the greater the force of the anchor cable and the formation of a stress arch with a base point at the two corners. The formation of the stress arch weakens the transfer of external pressure to the interior, reducing the asymmetric subsidence of the roof and horizontal extrusion deformation [99]. The anchor cables are connected by the high-strength steel support beam, which is more flexible to adapt to extrusion deformation and can prevent the connection structure from failing due to horizontal dislocation of surrounding rock. Increasing the internal hole size of the channel steel can reserve the deformation space for horizontal movement and avoid the stress concentration between the channel steel and the anchor cable due to the horizontal movement of the rock stratum [100].

4.2.4. Anchor Cable + Channel Steel Support

In mining hard and thick main roof coal seams, there are some control problems, such as severe overburden activity and asymmetric deformation in the roof. Scholars have proposed the asymmetric combined control technology of the roof with anchor cable–channel steel combination [101]. Figure 24m,n shows that each row contains four or five anchor cables. The anchor cables near the two ribs are deflected outward by 15°, and the anchor cables in the middle position are arranged perpendicular to the roof. Figure 24p is the supporting principle diagram.

4.2.5. Step Bundled Anchor Cable Support

For the roof support of ultra-thick coal seams (up to 15 m), some scholars have proposed the supporting technology of step-bundled anchor cables, as shown in Figure 24q,r. Moreover, the step bundle anchor cable comprises 5 anchor cables and a bundle anchor cable tray arranged in a "2-1-2" manner. The center is a 22 mm × 10,300 mm anchor cable surrounded by two 22 mm × 6300 mm and two 22 mm × 8300 mm anchor cables. The anchor cables are arranged diagonally and connected by a porous tray [32], as shown in Figure 24s [32].

4.3. Support under Difficult Conditions such as a Broken Roof

Figure 25 depicts an early support form of roadway driving along the goaf, primarily shed support, including I-steel and U-steel support. Secondary or multiple mining may influence the roads during layered mining and the mining of coal seam groups, and the deformation and failure of the surrounding rock are severe. The shed support and steel mesh combination can effectively limit the roadway's severe deformation. At the same time, it can improve the stress environment and the mechanical properties of the surrounding rock with a high-strength grouting anchor cable, indirectly improve the majestic residual strength and self-bearing capacity, significantly slow down the large deformation of the surrounding rock, and ensure the stability of the surrounding rock [33].

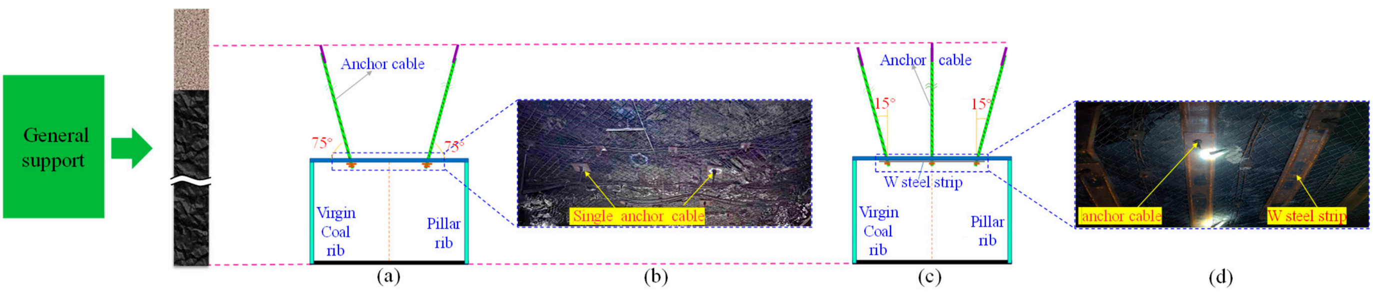


Figure 24. *Cont.*

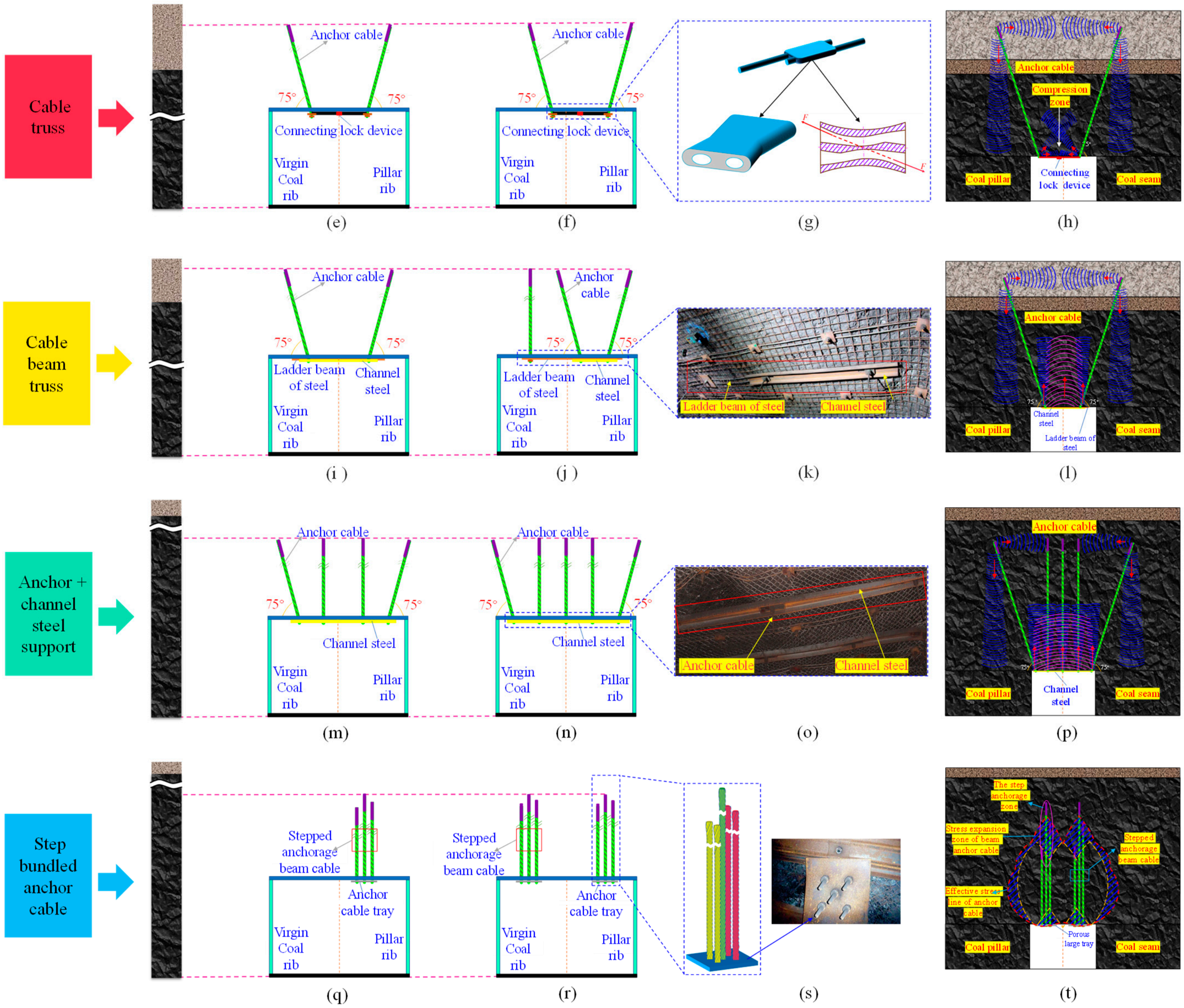


Figure 24. The roof support of gob-side entry driving: (**a**) single anchor cable support, (**b**) on-site support diagram, (**c**) anchor cable + W steel strip support, (**d**) on-site support diagram, (**e**) symmetric cable truss support, (**f**) asymmetric cable truss support, (**g**) connecting lock device, (**h**) supporting principle diagram, (**i**) asymmetric double anchor cable support, (**j**) cable truss + single anchor cable support, (**k**) on-site support diagram, (**l**) supporting principle diagram, (**m**) channel steel + four anchor cables support, (**n**) channel steel + five anchor cables support, (**o**) on-site support diagram, (**p**) supporting principle diagram, (**q**) single-step bundled anchor cable support, (**r**) step bundled anchor cable support, (**s**) stepped anchorage beam cable, and (**t**) supporting principle diagram. (**f**) [96], (**h**) [97,98], and (**m**,**n**) [101].

A single support method in the gob-side entry of fully mechanized caving often cannot meet the support requirements. Therefore, the combined support form with an anchor cable support as the core and other support methods (bolt, metal mesh, etc.) is often used to achieve adequate control of the surrounding rock, as shown in Table 1. The '√' in Table 1 represents the support form used in a certain spatial orientation of the roadway.

Table 1. Roof combined support table of gob-side entry driving in fully mechanized caving.

Support Position \ Support Pattern			**Bolt + Ladder Beam (W, JW Steel Strip) + Net**	**Single Anchor Cable**	**Anchor Cable + W, JW Steel Strip**	**Grouting**	**Roadway Side Concreate Wall**	**Gob Side Filling**	**Shelf**	**Anchor + Connecting Lock Device**	**Anchor + Channel Steel**	**Step Bundled Anchor Cable + Porous Large Tray**
Pillar rib		I	√									
		II	√									
		III	√			√	√					
		IV	√	√				√				
		V	√						√			
		...										
Virgin coal rib		I	√									
		II	√	√								
		III	√						√			
		...										
Roadway roof	General support		√									
	Anchor truss	I	√							√		
		II	√							√	√	
	Step bundled anchor cable		√		√							√
	...											
Special condition		I	√	√					√			
		...										

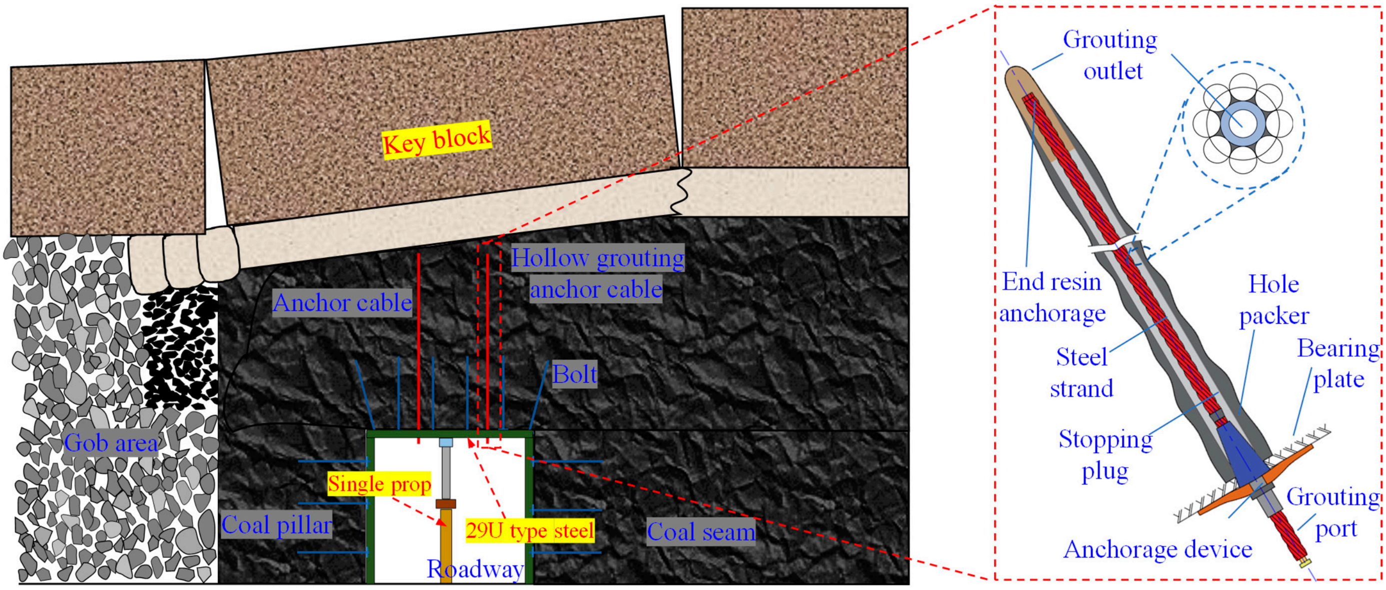
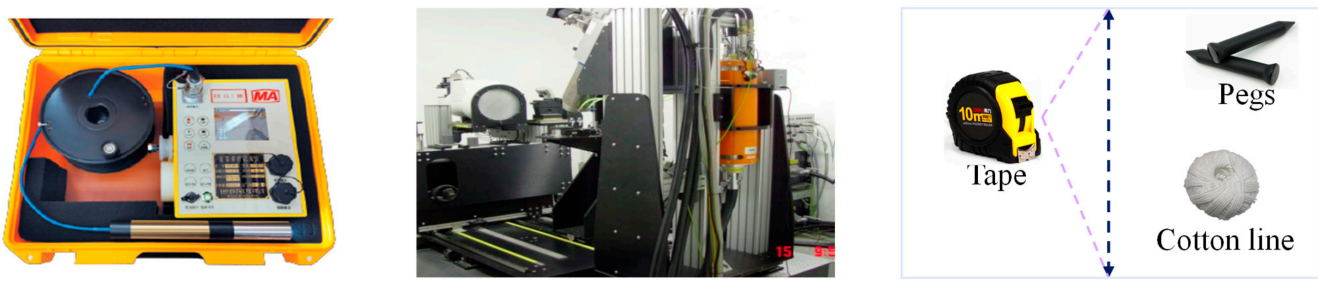


Figure 25. Shed support-grouting anchor cable cooperative support diagram [33].

5. Engineering Monitoring

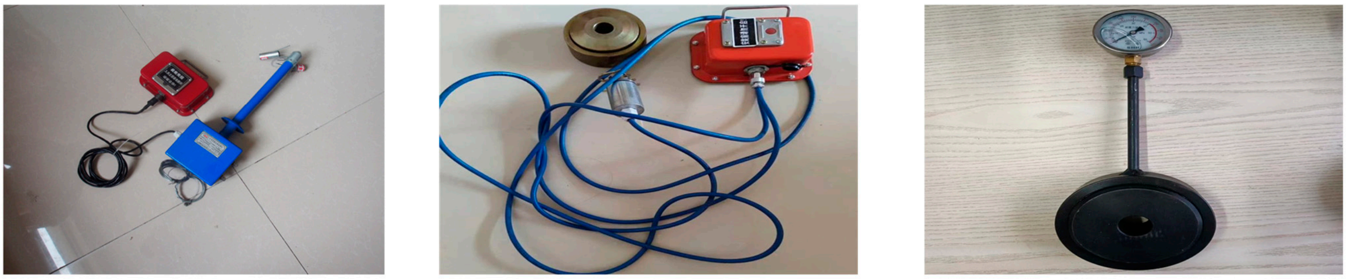
In addition to the above research, other scholars also analyzed the stress and deformation laws of surrounding rock in gob-side entry driving using field engineering monitoring.

The lateral roof structure type and lateral abutment pressure distribution characteristics were determined using microseismic monitoring and stress dynamic monitoring [44,102]. As a result, the deformation, failure mechanism, and control of fully mechanized caving roadway along the goaf were studied. The borehole peeping method was used to measure the main roof's fracture position and the roof's two-way movement characteristics. Combined with the CT identification of the asymmetric evolution process of the microcracks in the roof coal, comprehensive support technology was proposed [37,103]. In addition, to evaluate the feasibility of the support scheme and understand the working state of the support scheme in detail, the surface displacement of the roadway was monitored by arranging the measuring station; using the steel ruler and the measuring line, the separation sensor monitored the roof separation; the stress of the coal pillar was monitored with the borehole stress meter; and the bolt cable dynamometer monitored the working resistance of the bolt cable [104,105]. As shown in Figure 26, represents a variety of monitoring instruments.



(a) (b) (c)

Figure 26. *Cont.*



(d) (e) (f)

Figure 26. Engineering monitoring instruments: (**a**) detection equipment for internal fracture of the coal mass, (**b**) industrial CT scanning system, (**c**) roadway surface displacement monitoring equipment, (**d**) roof abscission layer instrument, (**e**) borehole stress gauge, and (**f**) anchor cable dynamometer.

6. Discussion

Gob-side entry driving is usually arranged at the edge of the goaf of the prior working face, retaining a certain width coal pillar (generally 5–8 m).

This paper summarized seven theoretical models of the overlying strata activity law and surrounding rock control in fully mechanized caving gob-side entry driving (the lateral breaking "large structure" model, compound key triangle block structure model in the middle and low position, the high and low right angle key block stability mechanics model, elastic foundation beam model, low-level combined cantilever beam + high-level multilayer masonry beam structure model, the vertical triangular slip zone structure model, the "internal and external stress field theory" and the "stress limit equilibrium zone model"). Three kinds of constitutive models (strain-softening, Mohr–Coulomb, double-yield) and numerical simulation methods were discussed. The support methods of coal pillar ribs, virgin coal ribs, and roofs of gob-side entry driving in a fully mechanized caving face are summarized. The following conclusions and prospects have been reached:

(1) With the wide application of gob-side entry driving without a coal pillar or with a narrow coal pillar, theoretical research on the activity law of the overlying strata and the stability control of the surrounding rock is gradually improved and developed. It lays a solid theoretical foundation for further promotion and application.

(2) Numerical simulation is an important technical means to study the problem of gob-side entry driving in fully mechanized caving. By selecting the appropriate constitutive model and numerical simulation software, the crack propagation morphology and plastic state in the coal pillar can be simulated, which can guide the reasonable location of gob-side entry driving and the design width of the coal pillar.

(3) The stability of the surrounding rock in the gob-side entry of fully mechanized caving is essential. On the side of the virgin coal rib, bolt cable support is often used with a ladder beam of steel (W, JW steel strip) and mesh. On the side of the coal pillar rib, it is mainly divided into three categories: anchor cable support, concrete wall support on the side of the roadway, and filling support on the side of the goaf; among them, the process of pouring a concrete wall and filling support is cumbersome and costly, which is only used under some special conditions. In the roof of the roadway, five kinds of support forms, such as anchor cable support, anchor cable truss support, anchor beam truss support, anchor cable + channel steel support, and step bundle anchor cable support, are often used. The roof often adopts a combination of multiple support methods. Under complete conditions, such as a broken roof, the deformation of the roadway is controlled by shed support, anchor cable grouting composite support, and other forms.

(4) Mine pressure monitoring is a research method often used in engineering. Understanding the stress and deformation law of surrounding rock in gob-side entry driving

is essential in optimizing the support design scheme using microseismic monitoring, dynamic stress monitoring, and borehole peeping for on-site engineering monitoring.

(5) Gob-side entry driving in fully mechanized caving is an important method of thick coal seam mining. In the future, we still need to strengthen the research on the basic theory to help us gain a more in-depth understanding of the various problems in gob-side entry driving. Further, we need to explore the nonpillar mining technology and develop more effective surrounding rock control technology to improve the recovery rate of coal resources in fully mechanized caving mining. In addition, the future method of gob-side entry driving with fully mechanized caving will also take into account precision, automation, and greening to realize safe and efficient mining of coal mines.

In this paper, we have summarized the relevant theories and technologies of gob-side entry driving in fully mechanized caving face and put forward that its future development direction should focus on theoretical research, nonpillar mining, and efficient surrounding rock control, which is helpful to promote the further development of gob-side entry driving technology in fully mechanized caving face.

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