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Study on Stress Characteristics and Supporting Countermeasures of Surrounding Rock in Roadway Formed by Composite Roof Cutting in Three-soft Coal Seam

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Abstract: *To effectively improve the stability of the surrounding rock in the roadway formed by composite roof cutting of a three-soft (soft roof, coal, and floor) coal seam, the force deformation characteristics of a roadway self-formed by roof cutting were analyzed through similarity simulation, numerical simulation, and field measurement under the engineering background of return air groove on 12406 working face in Selian No.2 Mine. The results showed that a significant pressure relief effect was achieved when the advanced supporting pressure periodicly moved forward to the presplit and cut roof, the stress concentration coefficient on the entity coal side was reduced by about 0.5, and the surrounding rock stress in the roadway was effectively improved. The surrounding rock deformation and the supporting force presented asymmetric distribution characteristics, the deformation rate exhibited a three-section law, and the stress in the gob displayed the recovery characteristic of circular progressive increase from the perimeter to the center. Considering the spatial geological conditions of this mine, a collaborative and integrated surrounding rock supporting countermeasure with "NPR constant-resistance anchor + hollow grouting anchor + retractable U-steel + floor bolting and grouting +door-like scaffold" as the core supporting structure was proposed. The results of the test section manifested that the surrounding rock deformation in the roadway was significantly educed compared with the original supporting scheme.*

Keywords: *Three-soft coal seams, Composite roof, Roadway formed by roof cutting, Surrounding rock deformation, Supporting countermeasure*

1. Introduction

During the successive mining of adjacent working faces, the next section of coal pillars will be generally retained after the previous working face [1] is mined to maintain the mining roadway of the next working face. Especially under high ground stress, an increasing greater width has been retained for coal pillars [2], most of which cannot be recovered, being the primary cause of coal resource losses [3]. To improve the recovery rate of coal resources, many experts and scholars have put forward small pillar mining [4] and mining through filling entry retaining [5], but they are still coal pillar mining in essence.

In contrast, the mining technology of gob-side entry retaining without coal pillars by roof cutting and pressure relief is a revolution of mining technology [6], which not only realizes the purpose of retaining no coal pillars but also blocks the stress transmission path between the gob roof and the roadway roof by roof cutting and pressure relief [7] so that the gob roof collapses itself to form a roadway by roof cutting. The stability of the surrounding rock in a roadway self-formed by roof cutting are affected by many factors, including roof and floor lithology of the working face [8], blasting-aided roof cutting parameters [9], and supporting parameters beside the roadway [10]. With the rapid development of high-strength anchor bolt supporting materials in recent years, the gob-side entry retaining technology that performs supporting by anchor bolts as the main materials has achieved a favorable application effect [11], the surrounding rock control technology of gob-side entry retaining without coal pillars has been greatly improved.

Despite the many advantages of the gob-side entry retaining technology through roof cutting and pressure relief without coal pillars, this does not mean that the coal pillar-free roof-cutting roadway

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formation technology is applicable in all cases, and its application depends on engineering geological conditions to a great extent. With the return air groove on 12406 working face in Selian No.2 Mine as an example, the undercover construction is frequent since the roadway roof is not supported, accompanied by serious rotary subsidence of the inappropriately supported composite roof, which further leads to the fracture of the gangue-retaining supporting structure. Under the specific geological conditions of 12406 working face in this mine, therefore, it is necessary to master the strata pressure behaviors in the roadway formed by roof cutting and optimize the surrounding rock control scheme, so as to provide reference for the further promotion of the coal pillar-free roof-cutting roadway formation technology.

2. Engineering background

The 12406 working face in Selian No.2 Mine is 389.93- 397.4 m in buried depth, 266 m in strike length, 2,824 m in dip length, and 1° in dip angle. The north side of the working face is adjacent to the 12407 gob, and the spacing of waterproof coal pillars is 21 m on the two working faces. To reduce coal resource loss and realize the goal of mining without coal pillars, the south cut-through 12405 working face will be mined using the "110 construction method" together with this working face, which share a return air groove through the roof-cutting roadway formation technology. The immediate roof and the immediate bottom are sandy mudstone, and the thickness is 3.5m and 6.13m respectively. The main roof and the old bottom are fine sandstone, and the thickness is 9.2m and 13.6m respectively. The supporting parameters of the surrounding rock section is shown in Figure 1.

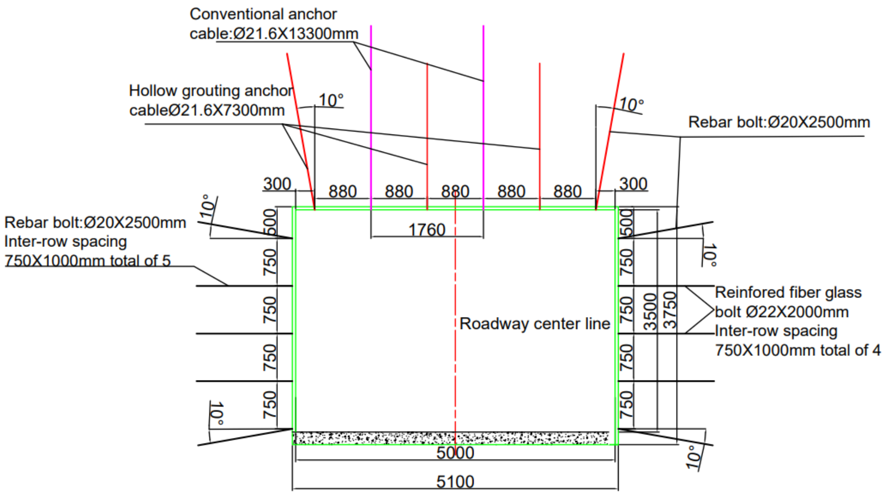

Figure 1: Charge structure and surrounding rock support parameters

3. Similarity simulation study

3.1 Establishment of similar model

As shown in Figure 2, the geometric similarity ratio of the design model is 50:1, the bulk density similarity ratio is 5:3, and the stress similarity ratio is 250:3, river sand as the aggregate, lime and gypsum as the cementing agent, and mica powder as the layered material were evenly mixed and paved layer by layer to form a similar model with dimensions of 3 m (length)×0.3 m (width)×1.41 m (height). Displacement monitoring points were arranged transversely and longitudinally on the model surface at an interval of 10 cm to monitor the displacement. In addition, pressure cells were placed at the immediate roof along the working face at an interval of 10 cm to monitor the stress change of overlying strata during the mining of the working face whose dimensions were 300 cm (length)×30 cm (width)×7 cm (height), boundary coal pillars were put at left and right 40 cm from the boundary, the two roadways (length× height=10 cm×7 cm) on the working face were arranged next to the boundary coal pillars, and the mining depth of the working face was 200 cm. Roof cutting was simulated by inserting steel plates (length× width× height=300 mm×1 mm×240 mm), which were located on the mining wall of the return air groove and inclined to the working face side in an angle of 15° with the plumb line, into the rock formation.

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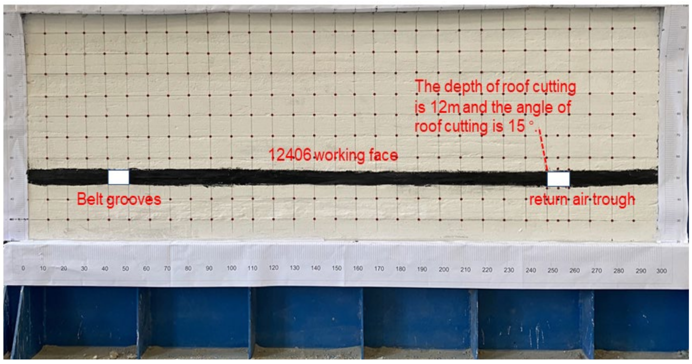

Figure 2: Overall graph of similar model

3.2 Analysis of similarity simulation results

3.2.1 Analysis on the fracture characteristics of overlying strata in roadway formed by roof cutting

As shown in Figure 3, when the working face advanced continuously to the presplitting and roof-cutting place, the gob roof collapsed along the presplitting face because of the loss of the support of the coal body, and the rock mass crushed and filled to form a macadam roadway. Despite the small crushing degree of the macadam roadway block, the lumpiness was great, tending to generate a large impact force on the roadway and making it necessary to emphasize the design of a gangue-retaining supporting structure. A masonry hinged girder structure was formed at the relatively high-level rock formation in the fissure zone. As the intermediate bearing body between the upper-level and lower-level rock formations, this structure maintained the stability of overlying rocks to some extent. In addition, the overlying rocks at the roadway roof presented a short-cantilever beam structure due to the roof-cutting action, the stabilized roadway self-formed by roof cutting was relatively intact, the roof slightly inclined to the gob, and if supported, the roadway could continue to serve the next working face, thus verifying the feasibility of the coal pillar-free roadway formation technology based on roof cutting and pressure relief.

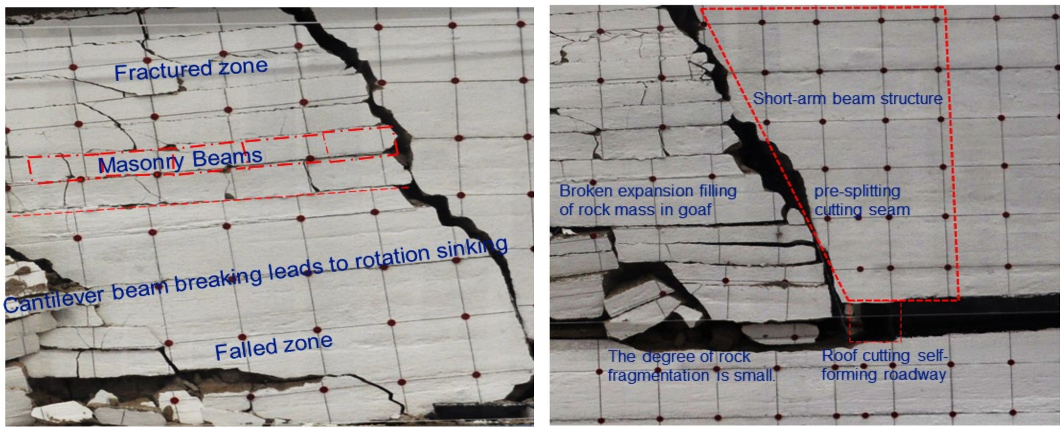

Figure 3: Overburden rock fracture characteristics of roof cutting roadway

3.2.2 Analysis on stress evolution characteristics of overlying rocks in roadway formed by roof cutting

As shown in Figure 4, the pressure relief effect of presplitting and roof cutting could be obtained indirectly by analyzing the stress evolution characteristics of the overlying rocks in the immediate roof. When the working face was mined to 20 m, the immediate roof was under a pressure relief state, the supporting pressure moved forward towards the coal wall, and a stress increase zone was located at about 10 m in front of the coal wall. When the working face was advanced to 0 m, the immediate roof reached the initial breaking span and collapsed. Afterward, the immediate roof caved with mining, the vertical peak stress in front of the coal wall reached 12 MPa, and the stress concentration coefficient was 1.2. With the continuous advancement of the working face, the gob roof was continuously subjected to pressure relief, and the supporting stress in front of the coal wall continuously experienced periodic forward shift until the working face was mined at 100 m of the presplitting and roof-cutting place. The stress of the overlying strata in the immediate roof decreased to 4 MPa, and the stress concentration

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coefficient was 0.4, indicating that the pressure relief effect of roof cutting was significant, which effectively blocked the stress transmission path between the gob roof and gob-side entry roof and improved the stability of the surrounding rock in the roadway.

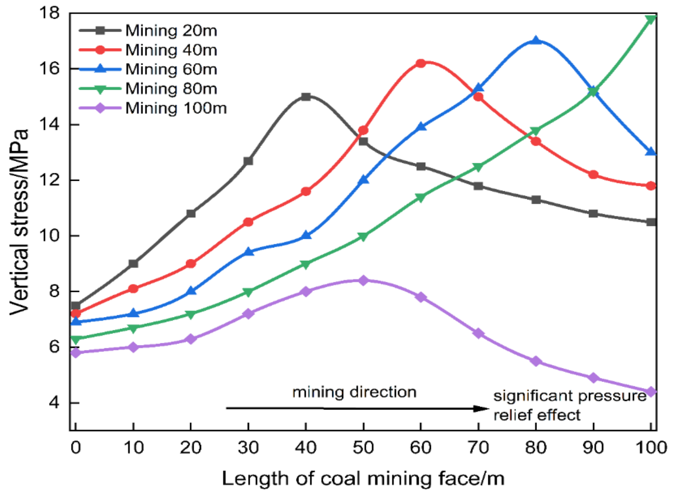

Figure 4: Stress variation curve of direct overburden rock

4. Numerical simulation study

4.1 Establishment of mathematical model

According to the actual engineering geological conditions, a mathematical model with dimensions of strike length (axis X) × dip length (axis Y) × height (axis Z) =310.6 m×400 m×71.69 m was established via FLAC3D. Boundary coal pillars were arranged within 50 m from the boundary around the model. The size of the belt groove on the working was length × height=5.6 m×3.5 m, that of the return air groove was length × height=5 m×3.5 m, and that of the working face was length× width × height=200 m×300 m×3.5 m. The roof-cutting depth on the return air groove side was 12 m, the roof-cutting angle was inclined to the working face by 15°, the Mohr-Coulomb constitutive model was adopted, fixed constraints were applied to the model perimeter and bottom boundary, and a vertical stress of -9 MPa was applied to the top boundary to simulate the load of the overlying strata. In addition, a horizontal stress with a lateral pressure coefficient of 1.2 was applied around. The physical and mechanical parameters of rocks are listed in Table 1.

Table 1: The physical and mechanical parameters of rocks

Lithology	Density (kg/m^3)	Young's modulus (GPa)	Poisson Ratio	Tension (MPa)	Cohesion (MPa)	Friction (°)
fine sandstone	2644	14.80	0.22	2.38	6.48	35.42
sandy mudstone	2640	8.10	0.30	1.85	2.32	37.78
coal	1356	2.47	0.33	1.32	1.62	24.53
siltstone	2648	9.80	0.25	1.94	3.40	38.29

4.2 Analysis of numerical simulation results

4.2.1 Analysis of stress distribution characteristics in stope

As shown in Figure 5, the numerical model stress data was imported into Tecplot for post-processing after the working face was mined, and the vertical tress slice 1 m above the roof was intercepted along the dip direction. It could be known by analyzing the stress distribution characteristics of the stope that the vertical stress in the gob of the working face exhibited the stress recovery characteristic of circular progressive increase from the edge to the center. The central vertical stress reached 6 MPa after the gob was slowly compacted, recovering to 60% of the primary rock stress of 10 MPa, while the vertical stress at the edges around was small, only recovering to 20-40% of the primary rock stress. This revealed that

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the compaction degree of central gangues was high, while that at edges was low. The lateral supporting pressure around the working face increased to different degrees, the lateral vertical stress of the working face without roof cutting was 34 MPa, while the vertical stress at the right side after blasting-aided roof cutting declined to 28 MPa, indicating that roof-cutting pressure relief could effectively block the stress transmission path between the gob roof and gob-side entry roof, so as to reach the effect of improving the stress environment of the surrounding rock.

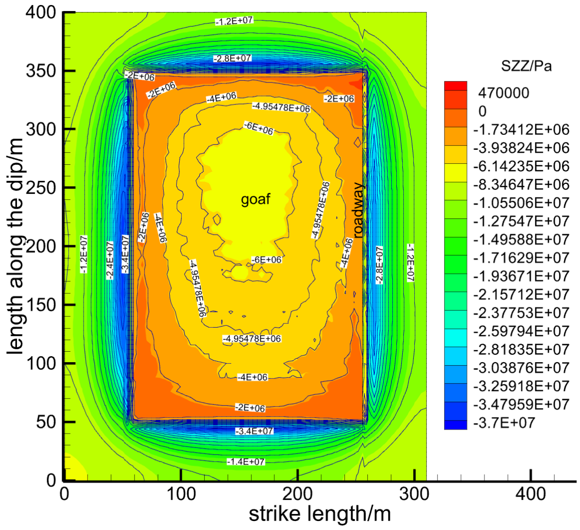

Figure 5: Stope vertical stress distribution

4.2.2 Analysis of mechanical deformation characteristics of roadway

As shown in Figure 6, it could be known by analyzing the stress law of the door-like scaffolds in the roadway self-formed by roof cutting behind the working face that: under the action of mine pressure, the roadway roof experienced rotary subsidence towards the gob so that the supporting force of door-like scaffolds presented an asymmetric distribution, namely, the stress borne by the scaffolds close to the gob side was greater than that close to the entity coal side. With the advancement of the working face, the force borne by the door-like scaffolds within 40 m behind the working face increased slowly. Beyond 40 m behind the working face, the stress borne by door-like scaffolds significantly increased, indicating that in this case, the upper roof of the working face reached the breaking span and collapsed, resulting in the sharp increase in the supporting pressure of scaffolds. Lagging behind the working face by over 260 m, the stress borne by door-like scaffolds started declining slowly, manifesting that this section already exceeded the zone of influence of dynamic pressure, the gob behind the working face was gradually compacted, and the roadway gradually tended to be stable.

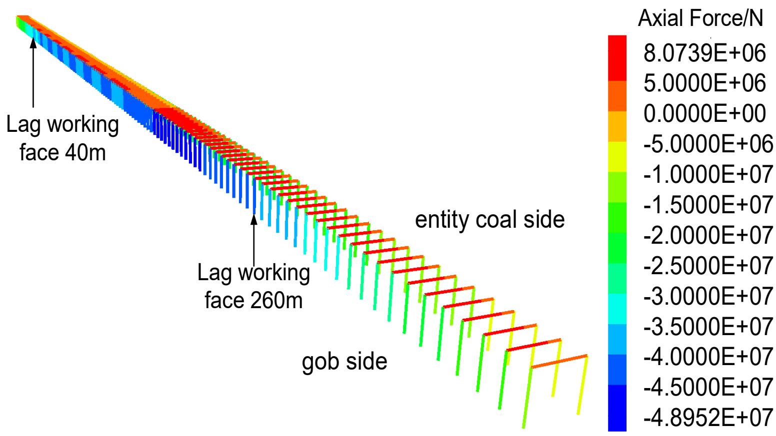

Figure 6: Axial force distribution of door-like scaffolds

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5. Field measurement and analysis

5.1 Analysis of supporting stress of door-like scaffolds

As shown in Figure 7, it could be seen that the supporting stress of the left and right stand columns of door-like scaffolds within 300 m behind the working face fluctuated within 10-40 MPa, and the supporting stress close to the gob side was greater than that on the entity coal side on the whole. After the lagging distance from the working face exceeded 260 m, the supporting stress of both left and right columns of door-like scaffolds substantially dropped, manifesting that the roadway already gradually tended to be stable in this case, which basically accorded with the numerical simulation result. This asymmetric supporting force characteristic was attributed to the rotary subsidence of the roadway roof after the working face was stoped out. Therefore, the emphasis of entry retaining should be laid on reinforcing the supporting strength of the roadway roof in the gob so as to inhibit the rotary subsidence of the roof and reach the effects of reducing the supporting resistance of the roadway and the deformation of the surrounding rock and enhancing the stability of the surrounding rock in the roadway.

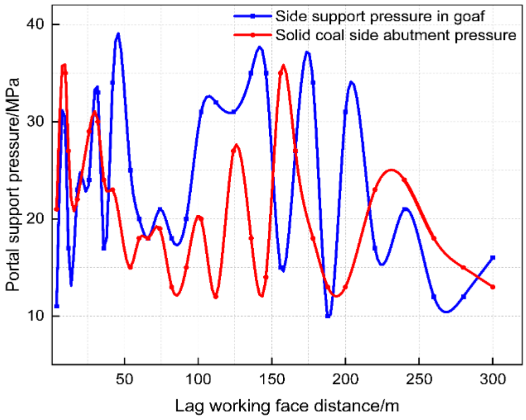

Figure 7: Abutment stress curve of door-like scaffolds

5.2 Deformation and failure analysis of surrounding rock in roadway

It could be known from Figure 8 that under the original roadway surrounding rock supporting scheme, a poor control effect on the surrounding rock of the roadway self-formed by roof cutting was obtained, accompanied by serious rotary subsidence of the roadway roof towards the gob side and serious inclination of door-like scaffolds close to the gob side. Given the poor supporting effect on the roadway roof, the pressure borne by the roadway wall was too large when the roof pressure was transferred to the roadway wall, resulting the fracture of U-steel on the gangue wall side. When the roof pressure further transferred to the floor through the roadway wall, since the roadway floor was relatively soft sandy mudstone and not effectively supported, sludge was seriously overstocked in case of large water accumulation, along with intense roadway floor heave, and the later-stage undercover construction was frequent, consuming a lot of manpower and material resources and making it urgent to reasonably optimize the existing surrounding rock supporting schemes.

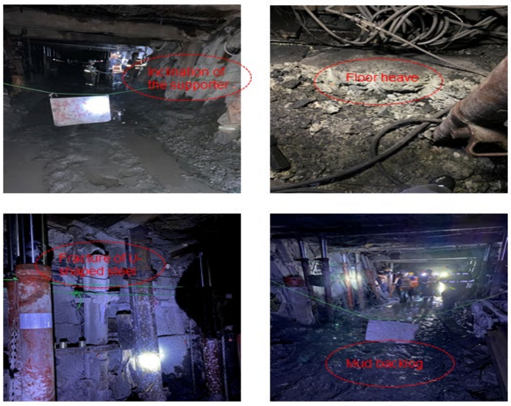

Figure 8: Stress failure mode of surrounding rock of roadway

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6. Surrounding rock control countermeasures of roadway

6.1 Optimization of surrounding rock supporting schemes for the roadway

1) “NPR constant-resistance large-deformation anchor cable+ hollow grouting anchor cable +W-steel belt” roof supporting

NPR constant-resistance large-deformation anchor cables have the advantages of constant working resistance, anti-disturbance energy absorption, and adaptability to large deformation, while hollow grouting anchor cables can reinforce soft rock strata, all of which, if comprehensively applied to the gob-side roof of the roadway self-formed by roof cutting, can exert a good supporting effect. Therefore, two columns of NPR constant-resistance large-deformation anchor cables with specifications of Φ21.6×13300 mm were designed and arranged. In addition, three columns of hollow grouting anchor cables with specifications of Φ21.6×7300 mm were laid out. The first column of NRP constant-resistance anchor cables was placed 500 mm away from the mining wall and the whole column along the roadway centerline. The first column of hollow grouting anchor cables was arranged 1.5 m away from the mining wall, the second column 3.5 m away from the mining wall, and the third column 4.5 m away from the mining wall. The array pitch of all anchor cables was 1,000 mm, specifically as shown in Figure 9.

2) “Grouting anchorage+ concrete level ground +installation of ground beams” floor supporting

For the sake of cost saving, the floor is generally not supported, and only the floor heaving phenomenon is handled through undercover construction, but much water is accumulated on the field with much floor sludge, which makes it inconvenient for the operation of constructors. If supporting is not appropriately done, the later-stage undercover construction will be frequent, consuming a lot of manpower and material resources and making it necessary to reinforce the floor stiffness. In the process of design, levorotary high-strength deformed steel bars (Φ20 mm×2500 mm) without longitudinal bars were adopted, the array pitch was 1500 mm×1000 mm, and the pre-tightening force was not lower than 70 kN. The array pitch of floor grouting holes was 1500 mm×2000 mm, the grouting holes on both sides were 500 mm away from the roadway wall with a diameter of 45 mm, a hole depth of 3,000 mm, and grouting pressure of 3-5 MPa. After grouting was finished, C30 concrete level ground 300 mm in thickness was paved to strengthen the stiffness of the floor surface. In addition, ground beams were installed beneath the stand columns of door-like scaffolds to evenly transfer the roof pressure to the floor and realize constant-pressure supporting of the floor, as shown in Figure 9.

3) “Steel mesh+ impingement plate+ retractable U-steel” gangue-retaining supporting

At present, the main kinds of gangue-retaining supports include: I-beams, retractable U-beams, and roof-cutting supports. According to the buried depth, mining height, roof lithology, and other factors, different combined supporting structures were adopted in cooperation with steel meshes to control the macadam wall of the roadway. Among them, the “retractable U-steel + steel mesh” supporting structure is applicable to medium-thickness coal seams, large buried depth, large lumpiness of caving gangues, high mine pressure, and long compaction time, featuring with high strength, adaptability to large roof deformation, and high recycling rate. Therefore, steel meshes, with a diameter of 6.5 mm and a size of 1900 mm×1100 mm, were used, overlapped by 100 mm, and tied up using iron wires. The impingement plates used, which were about 10 m in length, were hung behind the end support and moved forward with the pull frame of the end support. The retractable U29 steel was 2500 mm in length and 500 mm in array pitch, the retractable upper and lower segments could be overlapped and connected using two calan pairs, which were 100 mm from the lap end, and the steel bottom was buried into the roadway floor by a depth of 250 mm, as shown in Figure 10.

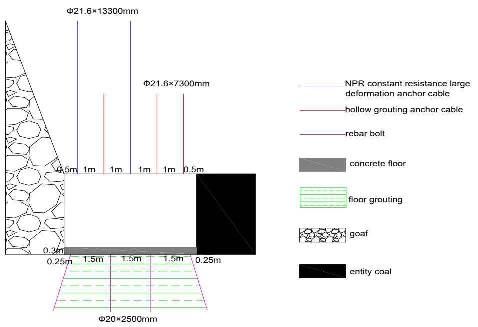

Figure 9: Roadway roof and floor support scheme

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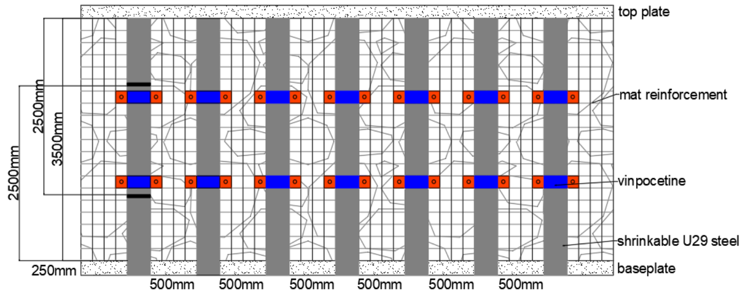

Figure 10: Roadside gangue retaining support scheme

6.2 Application effect of optimization scheme

Within 300 m of the test section of the roadway formed by roof cutting, the surrounding rock deformation under the optimization scheme was monitored using the cross-shaped point arrangement method, and the deformation curves as shown in Figure 11 were acquired. Under the comprehensive supporting effect of constant-resistance large-deformation anchor cables and hollow grouting anchor cables, the gob-side subsidence of the roadway self-formed by roof cutting was about 175 mm, with a reduction of 56% compared with that under the original supporting scheme, indicating that the composite roof strength was effectively reinforced and the suspension effect of anchor cables was fully exerted. Based on high-strength supporting of the roof, the soft rock floor was subjected to grouting and anchorage and the pavement of concrete level ground so that the floor stiffness was markedly enhanced and the floor deformation was significantly reduced. When the roadway was stable, the floor heave was about 200 mm, which was reduced by 66.7% compared with the situation without supporting. As the intermediate bearing bodies connecting the roof and the floor, two roadway walls played the role of transferring the roof pressure to the floor evenly. However, since the stress recovery of the broken gangue wall was relatively slow, the surrounding rock stress was transferred towards the deep part on the entity coal side so that the stress borne by the entity coal wall and its deformation were greater than those of the gangue wall. Nevertheless, the supporting pressure of the entity coal wall was reduced since the roof was effectively controlled, further reducing the deformation. In case of stability, the deformation of the entity coal wall was about 50 mm, which was reduced by 28.6% compared with the original supporting scheme, and the deformation of the gangue wall was about 20 mm, with a reduction of 20% in comparison with the original supporting scheme. To sum up, under this collaborative and integrated supporting countermeasure, the roof and floor displacement of the roadway self-formed by roof cutting was reduced by about 63.9% relative to that under the original supporting scheme, the displacement of the two walls was reduced by 27.8% compared with that under the original supporting scheme.

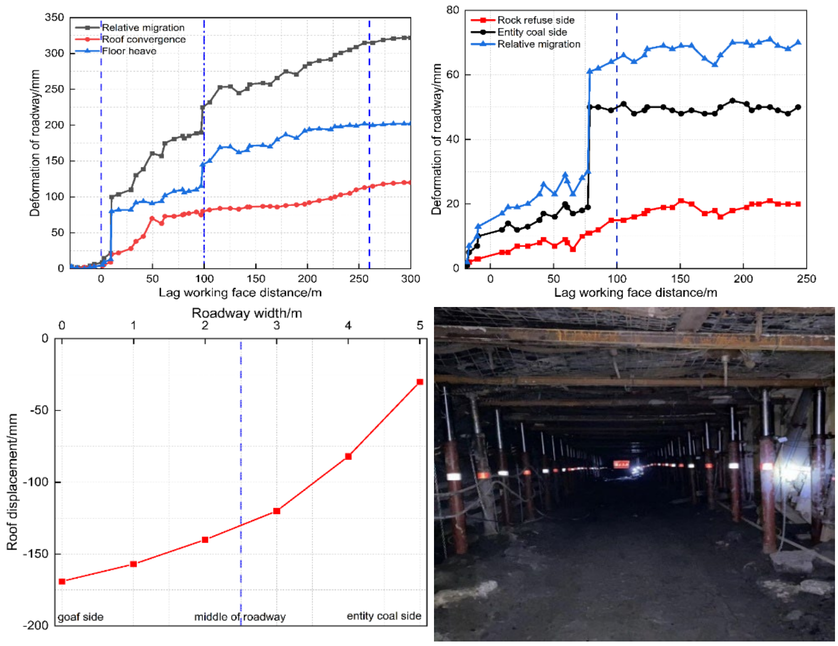

Figure 11: Deformation curve of roadway surrounding rock in test section

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7. Conclusions

1) In the mining process of the working face, the advanced supporting pressure presented a periodic forward movement characteristic, the pressure relief effect was significant when reaching the presplitting and roof-cutting part, the stress transmission path between the roadway and the gob roof was cut off, the stress concentration coefficient was reduced by about 0.5, the surrounding rock stress environment of the roadway was effectively improved, and the entry-retaining surrounding rock was favorably intact, proving the feasibility of the coal pillar-free gob-side roadway formation technology based on roof cutting and pressure relief.

2) The surrounding rock deformation and supporting force of the roadway self-formed by roof cutting presented an asymmetric distribution. The surrounding rock deformation was dominated by floor heave and roof subsidence. The stress in the gob showed the recovery characteristic of circular progressive increase from the perimeter to the center. In addition, the surrounding rock deformation rate of the roadway self-formed by roof cutting within 300 m behind the working face was divided into three sections

3) The rock stratum under the composite roof tended to be loose and broken easily. When the development depth exceeded the depth of the anchor cable, the anchor cable support would fail in a large area. The field test results show that the supporting scheme of “NPR constant-resistance and large-deformation anchor cable + hollow grouting anchor cables” can effectively improve the bearing capacity of the surrounding rock in the three-soft composite roof roadway, reduce the rotary subsidence of the roadway roof, and indirectly reduce the supporting pressure of the roadway wall and floor.

Acknowledgements

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