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Article

# Research on Roof Structure Model and Reasonable Support of GSER by Cutting Roof in Three-Soft Coal Seam

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**Abstract:** In order to reveal the deformation mechanism of surrounding rock in the three-soft coal seam with GSER(GSER), through physical simulation experiment, the roof strata fracture evolution under the three conditions of no roof cutting general support, top cutting high-strength support, and roof cutting public support is simulated, the roof structures mechanical structure model of roof cutting GSER in the three-soft coal seam is established. The research shows that based on the overburden characteristics in the three-soft coal seam, the roof-cut technology cuts off the stress transmission, and high-strength support is adept in the roadway. Therefore, the roof can form a "short cantilever beam-voussoir beam" structure. With no roof cutting general support, the average approach distance and the floor are 1000-1200mm. The moderate approach distance of the two sides is 600-700mm. Under the roof cutting general support, the middle approach distance of the roadway roof and the floor is 800-900mm. The intermediate approach distance of the two sides is 400-500mm. Under the roof cutting high-strength support conditions, the roadway roof and floor's average approach distance is 200-300mm, and the intermediate approach distance of the two sides is 200-300mm. Under the roof cutting combined support, the middle approach distance of the roadway roof and the floor is 50-100mm. The moderate approach distance of the two sides is 100-200mm. Therefore, the combined high-strength support can better control the severe

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deformation of the surrounding rock of the GSER in the three-soft coal seam. The remaining roadway can satisfy secondary reuse with no repair.

**Keywords:** three-soft coal seam; GSER by cutting roof; short cantilever beam-voussoir beam; combined hydraulic support; high-strength support

## 1. Introduction

Non-pillar mining is an important development direction of coal science and technology. Non-pillar mining in three-soft coal seam is a major problem of green, safe and efficient mining in deep mines [1-3]. The problem of GSER in three-soft coal seam is more prominent and needs to be studied urgently [4-10].

The coal pillarless mining technology of GSER has the advantages of improving the coal recovery rate, solving the gas accumulation in the upper corner of the working face, reducing the amount of roadway excavation and alleviating the tension of mining connection. It has been widely used. The key of GSER is to control the roof subsidence of gob-side entry, prevent the coal gangue from pouring into goaf and air leakage [11-15].

He Manchao proposed the theory of “roof-cut short arm beam” and the technology of two-way pre-splitting roof-cut retained roadway with energy accumulation. By using the mine pressure to work and the crushing and expansion characteristics of caving gangue, the roadway tunneling and coal pillar retained were cancelled, and the N00 mining system without coal pillar was formed (N working faces were mined, 0 roadway tunneling and 0 coal pillar retained) [16-18].

The above studies have enriched and developed GSER technology, but there are few studies involving GSER in three-soft coal seams. At present, the new technology applied to the GSER in the three soft coal seam mainly includes the soft concrete support technology and the roof cutting pressure relief technology. Both technologies have not fundamentally solved the problem of floor heave in the three soft coal seam roadway. Based on the roof cutting and pressure relief technology, this paper studied the roof structure and support resistance calculation method of roadway in three-soft coal seam through physical simulation and field measurement, developed high-resistance single prop and combined hydraulic support, and carried out a successful test in Xiangshan Coal Mine of Hancheng, realizing no rework of roof cutting and roadway retaining in three-soft coal seam.

## 2. Project Overview

The 21311 fully mechanized mining face in Xiangshan Mine of Hancheng Mining Company has a strike length of 1250m and a tendency width of 205m. The main coal seam is 3# coal seam with a thickness of 1.4m~3.55m and an average of 2.0m. The thickness of the pseudo roof of the working face is 0.1m~0.2m, the direct roof is silty mudstone, the thickness is 2.5m~4.5m, the old roof is siltstone, and the rock layer thickness is 4.5-6.0m.

The false bottom is not developed. The direct bottom of the coal seam is argillaceous cemented siltstone, which is medium-thick layered with a thickness of 3.8m~5.2m.
The 21311 auxiliary air intake lane has a rectangular section with a clear width of 4.4m and a clear height of 2.55m. The top slab is supported by anchor mesh and cable, φ22×6000mm anchor cables, 3 sets in a row, row spacing 1000mm, φ22×2400mm rebar anchor rods, 5 in a row, row spacing 800mm. The coal bank is supported by φ22×2000mm or φ22×3500mm full-length self-consolidating bolts with diamond mesh, with a row spacing of 800×800 mm. The supporting section is shown in Figure 1.

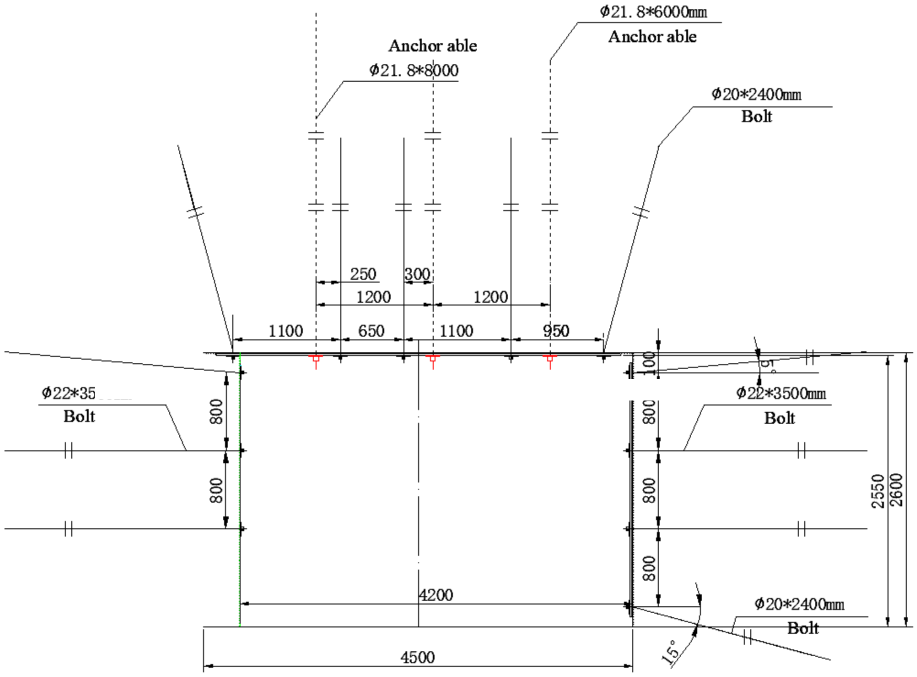


**Figure 1**. Supporting scheme of 21311 auxiliary entry

It is found through field measurement that the 21311 auxiliary air intake roadway adopts the combined support of "anchor mesh cable + single hydraulic prop". Compared with the adjacent 21310 working face adopting the traditional way of leaving roadway along the goaf, the roadway surrounding rock has large deformation and the supporting effect Difference. During the lane retention period, the roadway deformation enters a stable stage after the working face is advanced for 300m. The roof subsidence is 230mm on average, the bottom heave deformation is 800-1000mm on average, the convergence of the two sides is 635mm on average, and the overall convergence rate of the retained laneway section is as high as 54.9%. It can be reused after pulling the bottom twice.
The main reason for the deformation of the top and bottom of the roadway is that the bottom mudstone is softened by water, and the single pillar is inserted into the bottom to relieve the pressure and lose the supporting effect. The main reason for the greater convergence of the two banks is that the coal seams are soft (the f coefficient is 0.3-0.4). Under the influence of mining pressure, the coal seams of the two banks are deformed and damaged seriously, which causes the anchor rod tray to be embedded in the coal bank and lose its supporting effect. Lane reserved along the goaf presents the characteristics of a

large bottom heave volume, a second approaching amount of the two sides, and a small amount of roof subsidence, as shown in Figure 2.

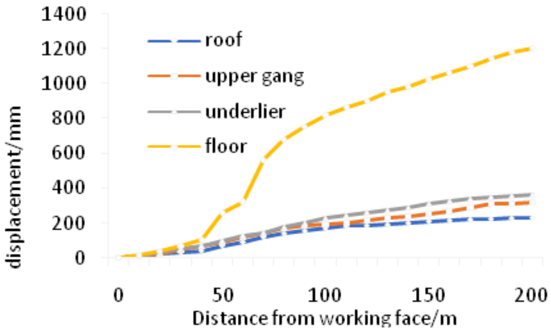


**Figure 2.** The surface deformation curve of original roadway

## 3. Roof Breaking Structure Characteristics of Roof Cutting Retaining Roadway

### 3.1 Physical Similarity Simulation Model Construction

Taking the 21311 working face of Xiangshan Coal Mine as the object, the experiment was carried out with a large ratio of geometric similarity ratio of 1:100 [20]. According to the geometric similarity ratio, a plane stress model frame with a length of 300 cm, a width of 20 cm, and a height of 150 cm is used to pave the model. Considering the lithology and raw material property, during model set up, sand was used as the aggregates, gypsum and calcium carbonate were adopted as cementitious materials, mica powder was used to simulate tectonic fissure. In the same model, compare three roadway schemes without roof cut, ordinary support with cut-to-production ratio of 3.25 and high-strength support with cut-to-production ratio of 3.25, as shown in Table 1. Leave a 40cm (equivalent to prototype 40m) boundary on the left side of the model, and mine to the right to observe the roof structure and movement characteristics under different cut-to-production ratios and support conditions. The experimental panoramic model is shown in Figure 3.

**Table1** Experimental program

| plan | Mining Height（m） | Cutting ratio | Support Pattern |
|---|---|---|---|
| 1# | 2 | 0 | General support |
| 2# | 2 | 3.25 | High strength supporting |
| 3# | 2 | 3.25 | General support |

### 3.2 Analysis of Overburden Migration

The model excavates from left to right to simulate the mining process of the working face. After mining, the direct roof collapses with mining, and the collapse height is 2.3m. When the working face was advanced to 35m, the basic roof broke for the first time, the roof collapsed at a height of 12m, and the basic roof overlying the roadway appeared asymmetrically broken. With the advancement of the working face, the roof enters the periodic breaking stage. The first periodic break occurs at 51.4m, with a step distance of 16.4m; the first periodic break occurs when it advances to 109.9m to achieve full mining. A total of 5 periodic breaks occur with an average step distance of 12.8m.

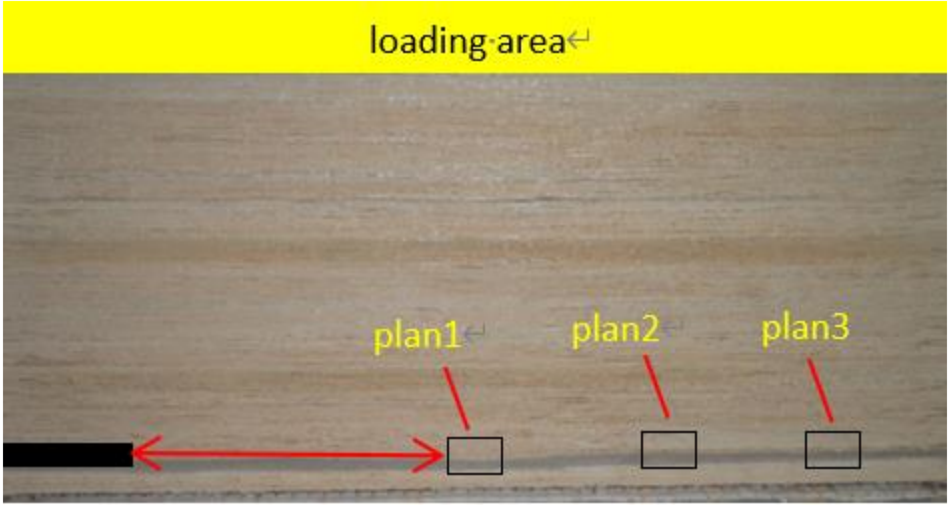


**Figure 3**. Experimental model panorama

(1) Uncut roof ordinary support GSER

In order to grasp the formation process of the roof structure of the roadway without pillars along the goaf, the roadway was first excavated at a distance of 30m from the side of the working face (no mining affected area), and the coal pillars were excavated after the roadway was stabilized. The breaking rules of the roof are as follows:

Roof rotation stage: Basically, the goaf revolves and sinks in the top direction, showing a long cantilever structure;

Roof breaking stage: With the basic roof rotating, the sinking intensifies, and vertical conductive cracks are formed in the upper part of the roadside coal wall;

The roof cut-off stage: the roof breaks along the roadway, as shown in Figure 4.

The simulation shows that the use of uncut roof and pillarless mining will not form a stable hinged structure after the roof of the roadway is broken, and the cut-off damage along the coal wall will occur, which seriously threatens the safety of the roadway.

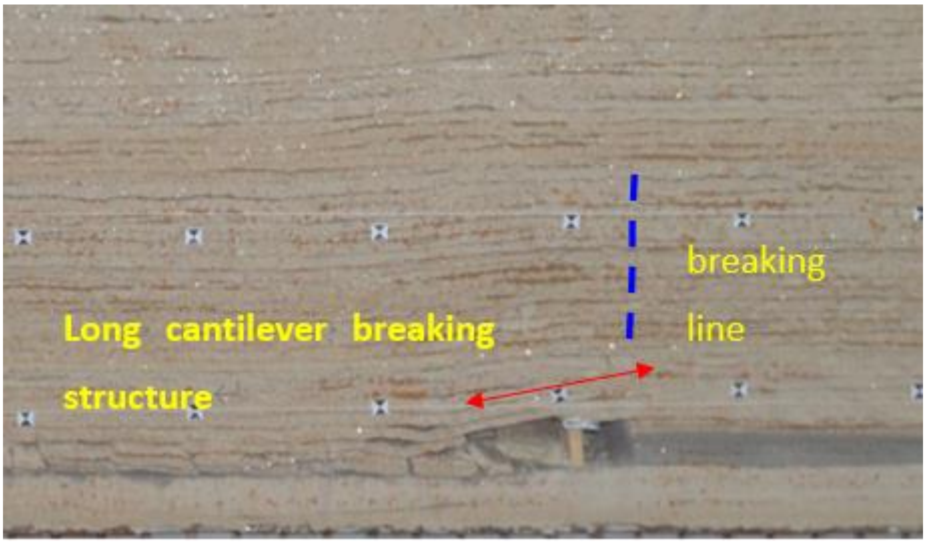


**Figure 4.** Long cantilever structure

(2) Top cutting high strength single support GSER

After the plan 1 ends, the roadway is excavated according to the plan 2 position, the roof is cut and the roadway is retained according to the roof cutting angle of 15°, and the coal pillars are excavated after the roof is stabilized to simulate the process of roof cutting and roadway retention. High-strength support is used in the roadway to simulate the strong support of single pillars and combined hydraulic supports. After the coal pillar is excavated, the basic roof outside the cutting roof height range is broken. The key block and the broken rock mass in the goaf and the upper rock mass of the roadway form a stable masonry beam structure, forming a "short cantilever" with the lower cutting roof control layer "Beam-masonry beam" structure, as shown in Figure 5.

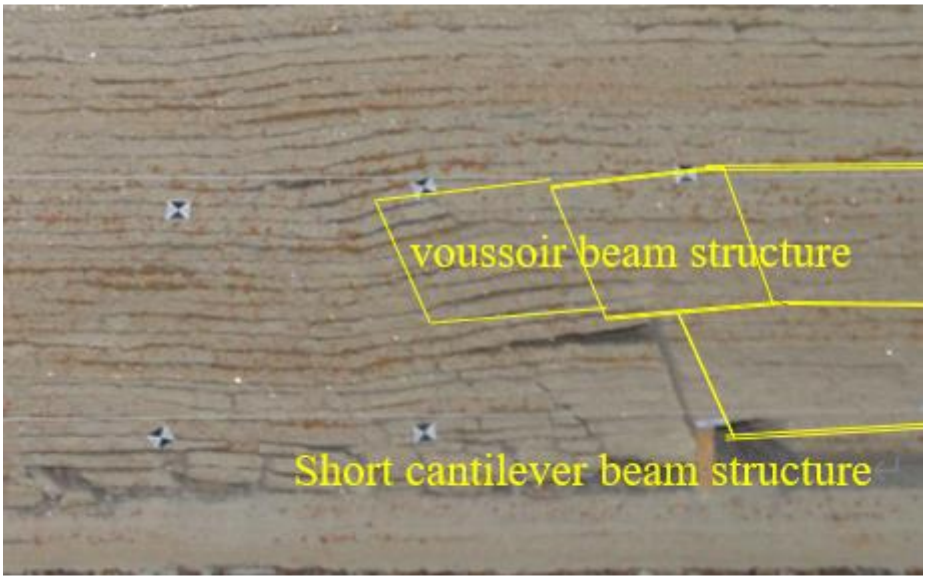


**Figure 5**. Short cantilever beam-voussoir beam structure

(3) Common roof cutting support GSER

After the end of mining in Scheme 2, the roadway was excavated according to Scheme 3, and the roof was cut according to the roof cutting angle of 15° and the cutting-to-mining ratio of 3.25. The coal pillar was excavated once after the roof cutting retained roadway was stable. The role of roof cutting in the process of retaining roadway and its influence on roof structure were compared.

After the coal pillar excavation, due to the weak support, the top-cutting control layer appears in the form of ‘short masonry beam’, and the upper basic roof breaks in deeper depth, forming the hinged structure of masonry beam. To sum up, the roof formed a ' short masonry beam-masonry beam ' structure when the roof cut ordinary support retaining roadway along goaf, as shown in Figure 6.

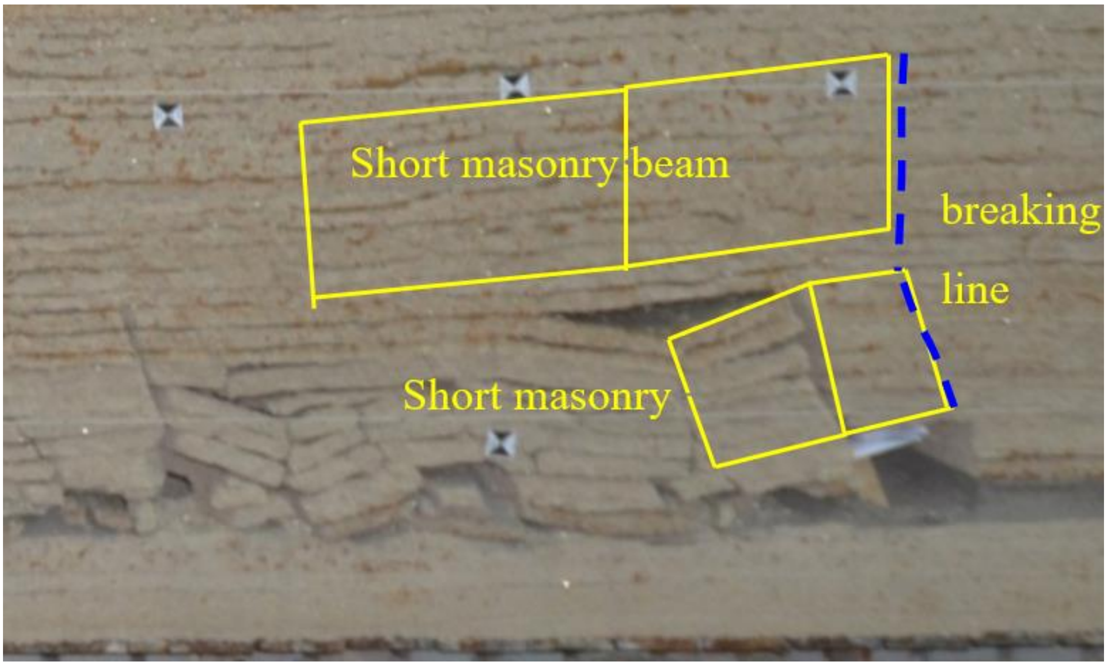


**Figure 6**. Short voussoir beam-voussoir beam structure

## 4. Mechanical model analysis of roof structure

### 4.1. Mechanical model of roof structure

In the early stage of GSER without coal pillar roof cutting, the roof cutting control layer and the basic roof form a 'short cantilever beam-masonry beam' structure. The short cantilever beam structure has bearing capacity and improves the stability of roadway. Based on the above analysis, the mechanical model of 'short cantilever-hinged' roof structure in GSER is established, as shown in Figure 7.

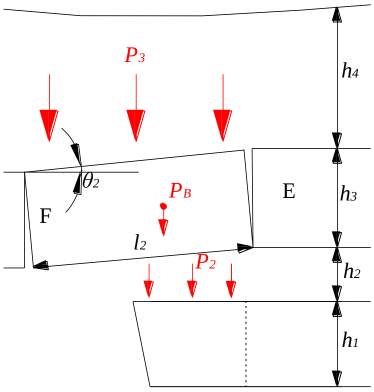


**Figure 7**. Mechanical model of short cantilever beam-voussoir beam structure

The condition for the formation of a short cantilever beam by the top-cutting control layer is that the overlying load of the short cantilever beam is less than its own carrying capacity. Short cantilever beam force mainly includes basic top weight PB, basic top overburden load P3, soft interlayer load W2. The analytical calculation process is as follows:

1) Force of overlying strata on basic roof

$$P_3 = K_G l_2 \sum h_4 \gamma_2 \tag{1}$$

$$K_G = \frac{l_2}{2h_3 \lambda_3 \tan\varphi} \tag{2}$$

$K_G$ is the load transfer coefficient. $h_4$ is the thickness of the basic top load layer, m. $\gamma_2$ is load layer density, kN / m$^3$.

2) Basic top force

The basic roof force is composed of the self-weight of the key block F of the basic roof and the force of the overlying strata. By introducing the calculation formula of masonry beam, we can obtain:

$$P_B = l_2(\sum h_3\gamma_1 + P_2)[\frac{4i_2 - 3\sin\theta_2}{2(2i_2 - \sin\theta_2)} - \frac{\tan\varphi_2}{i_2 - \sin\theta_2 + 2\sin\theta_2}] \tag{3}$$

Among them, $h_3$ is the basic top thickness, m. $\gamma_1$ is the average bulk density of bedrock, kN / m$^3$.

3) Force of weak rock stratum

$$W_2 = l_1 \sum h_2 \gamma_1 \tag{4}$$

where h2 is the thickness of soft rock strata, m. l1 is the length of the top key layer, m.

4) Stress of short cantilever beam

$$P_2 = P_B + W_2 = l_2(\sum h_3\gamma_1 + P_2)[\frac{4i_2 - 3\sin\theta_2}{2(2i_2 - \sin\theta_2)} - \frac{\tan\varphi_2}{i_2 - \sin\theta_2 + 2\sin\theta_2}] + l_1 \sum h_2 \gamma_1 \tag{5}$$

It can be obtained from the above that the maximum shear stress $\tau_{max}$ of the top-cutting control layer, where the beam width b = 1, can be obtained:

$$\tau_{\max} = \frac{3l_2}{2h_1}(\sum h_3\gamma_1 + P_2)[\frac{4i_2 - 3\sin\theta_2}{2(2i_2 - \sin\theta_2)} - \frac{\tan\varphi_2}{i_2 - \sin\theta_2 + 2\sin\theta_2}] + \frac{1}{2i_2}\sum h_2\gamma_1 \quad (6)$$

4.2. Checking Calculation of Support Resistance of Roof- Retaining in Xiangshan Mine

The mining height of 21311 working face in Xiangshan Coal Mine is 2 m, and maintaining the stability of the short cantilever structure of the roof cutting control layer is the key to the roof structure control of the roof cutting retaining roadway and the purpose of high strength support in the roadway. During the mining of the working face, the roof rotation angle of the roof cutting control layer was 3°, and the lateral breaking distance of the basic roof was 7 m. The roof cutting retained roadway formed a "short cantilever-hinge" structure. According to References, the roof strata of 21311 working face take φ=35°, λ=1−sinφ =0.63. According to the load transfer coefficient formula, KG = 0.63.
Force of overlying strata on basic roof:

$$P_3 = K_G l_2 \sum h_4\gamma_2 = 13812kN \quad (7)$$

Basic top force:

$$P_B = l_2(\sum h_3\gamma_1 + P_2)[\frac{4i_2 - 3\sin\theta_2}{2(2i_2 - \sin\theta_2)} - \frac{\tan\varphi_2}{i_2 - \sin\theta_2 + 2\sin\theta_2}] = 4837\,\mathrm{kN} \quad (8)$$

Force of weak rock stratum:

$$W_2 = l_1 \sum h_2\gamma_1 = 254.4kN \quad (9)$$

The key layer force:

$$P_1 = \frac{1.7 - (1.2 + 4.6i_1)\tan\theta_1}{4 - 1.2\tan\theta_1}[l_2(\sum h_3\gamma_1 + P_2)[\frac{4i_2 - 3\sin\theta_2}{2(2i_2 - \sin\theta_2)} - \frac{\tan\varphi_2}{i_2 + \sin\theta_2}] + l_1\sum h_2\gamma_1] = 1014kN \quad (10)$$

Direct top force:

$$W_1 = l_1 \sum h\gamma_2 = 322kN \quad (11)$$

In summary, the minimum support resistance R value of GSER without coal pillar to maintain roof stability can be determined.

$$R \geq 1014 + 322 = 1336kN \quad (12)$$

The roof was supported by special high and anchor cable were used to support the roof in the field. The average working resistance during the mining period was 400 kN / column, and the monomer row spacing was 0.8 m. Three monomers were set in one row, and the pure support strength could reach 1500kN/m, indicating that the calculation results were consistent with the actual situation.

## 5. Roof Cutting Retaining Roadway Support Technology

### 5.1. High Resistance Single Hydraulic Prop Support Technology

In view of the characteristics of large floor heave in top cutting and retaining roadway in soft coal seam, a new type of high resistance single hydraulic prop is developed, and the resistance can reach 400 KN. The 'anchor cable + high resistance single hydraulic prop' is used in the roof cutting and retaining section. The single pillar models are DW2.8–400/110X(M) and DW3.15–350/110X(M).With 413×413×25mm large pillar shoes, one beam and three pillars are designed. The row spacing is 800mm–1000mm. The pillar supporting force is 22–24MPa, and the working resistance is 350–400kN. The high strength support section of the retaining roadway is shown in Figure 8.

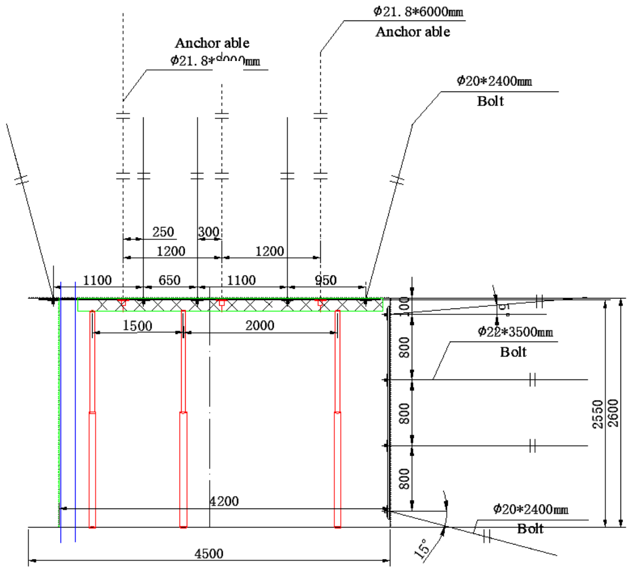


**Figure 8**. High-strength prop supporting scheme of 21311 entry retaining

Starting from the advanced working face 50 m, the supporting monomer is used to control the influence of advanced pressure, and then the high resistance monomer is continued to support in the retaining section to control roof subsidence and floor heave. After the GSER of 200 m lagging working face enters the stable stage, the monomer is gradually removed. According to the stability of roof and floor, one row is removed first, and then gradually removed after the roadway is stable.

During the advance support of high resistance single prop, the working resistance increases from 30 m ahead of the working face, and increases sharply from 10 m away from the working face. The peak value of 10–20 m behind the working face reaches 33–40 MPa, and then the resistance gradually drops back to 30 m behind the working face to reach stability (25–30MPa), as shown in Figure 9.

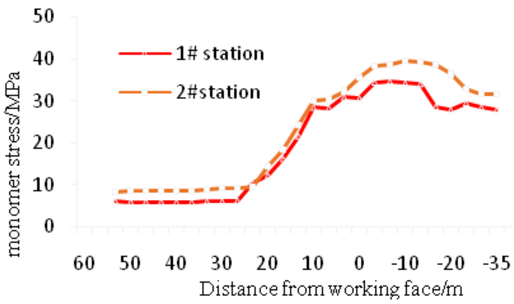


**Figure9**. Stress curves of high-strength prop

5.2. Supporting Technology of Combined Hydraulic Support

In view of the characteristics of large roof subsidence and floor heave of roadway in three soft coal seams, in order to ensure the safety of roadway support, picture of the combined hydraulic support and movable base is shown in Figure10, the support mode of ' combined hydraulic support + active base ' was also developed. The initial support force is 25MPa and the working resistance is 3500KN. In the test working face, 20 frames were installed and used, with two frames and one group, and the spacing of each group was 500 – 800 mm. The roof and floor were supported with the active base. The section diagram of combined support for retaining roadway is shown in Figure 11.

**Figure 10**.Picture of the combined hydraulic support

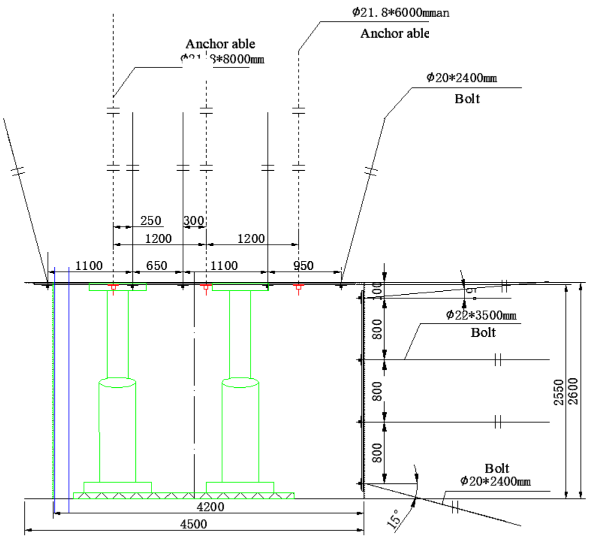


**Figure 11**. Combined hydraulic supporting scheme of 21311 entry retaining

By observing the support effect in the range of 50 m ahead to 200 m behind the working face, the variation law of combined support pressure is shown in Figure 12.Since the working face ahead of 10m composite support pressure began to rise significantly, working face within 20m support working resistance increased sharply, 20-100m behind the working face support resistance to maintain high operation, safety valve opening interval of 7-8m ( safety valve opening pressure40-42MPa ), pressure relief times are more frequent. After the working face lags behind 100 m, the change of support pressure tends to be gentle, and the mine pressure of roadway is stable.

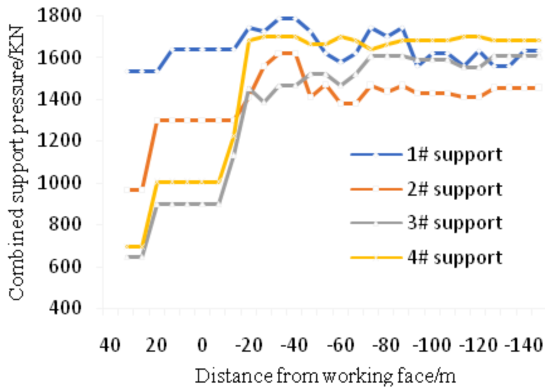


**Figure 12**. Stress curves of combined hydraulic support

5.3. Effect Analysis of Roadway Retaining

The length of the test section of the auxiliary intake roadway in 21311 working face is 1250m. Three support schemes are used to compare the effects. One is the ordinary single hydraulic support, the second is the high resistance single hydraulic support, and the third is the combined hydraulic support. three kinds of supporting way roadway two sides of the displacement curve as shown in Figure 13, roof and floor displacement curve as shown in

Figure 14. The results show that the average roof-floor convergence is 100mm−1200mm under the condition of ordinary single support, and the average two-side convergence is 600–700mm. Under the condition of high resistance single support, the average displacement of roof and floor is 200mm-300mm, and the average displacement of two sides is 200-300mm. Under the condition of combined hydraulic support, the average displacement of roof and floor is 50mm-100mm, and the average displacement of two sides is 100-200mm. The combined support has the best supporting effect on the roadway, which can better control the roof subsidence and floor heave of the roadway, and is suitable for the GSER support in the three-soft coal seam.

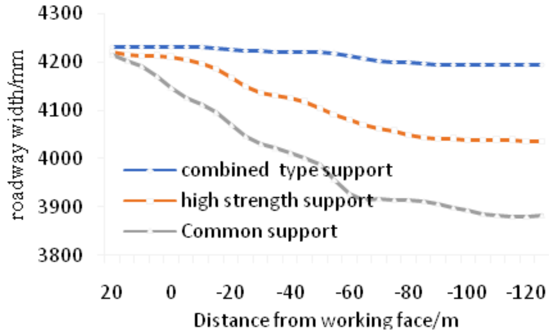


**Figure 13**. Contrast curve of roadway two-sided displacement

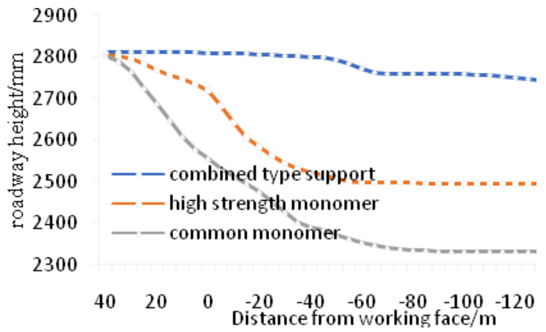


**Figure 14**. Contrast curve of approach distance of the roadway roof and floor

## 6. Conclusions

Through physical similarity simulation, the roof structure characteristics of three supporting schemes of GSER in soft coal seam were studied, including non-cutting roof common single support, cutting roof high resistance single support and cutting roof common single support. The ' short cantilever-masonry beam ' structure is formed under the condition of high strength support, which is a stable structure and conducive to roof control.

The ‘short cantilever-masonry beam’ structural mechanical model of roof cutting and retaining roadway is established, and the calculation formula of roadside support resistance is given. The field test shows that the calculated high-strength support resistance fully meets the requirements of roof cutting and retaining roadway in three soft coal seams.

At present, the new technology applied to the GSER in the three soft coal seam mainly includes the soft concrete support technology and the roof cutting pressure relief technology. Both technologies have not fundamentally solved the problem of floor heave in the three soft coal seam roadway. In order to solve the problem of serious roof subsidence and floor heave in GSER in soft coal seam, high strength single pillar and combined hydraulic support support technology are developed. Through field industrial test, the high-strength single pillar can effectively control the deformation of roadway surrounding rock, and the roof-floor convergence is reduced from 1000–1200mm to 200–300mm. The support effect of combined hydraulic support is more obvious, and the displacement of roof and floor is reduced to 50-100mm, which realizes the goal of ' primary roadway completion without repair in GSER.

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