Surrounding rock deformation and supporting measures on small structure in non-pillar mining with gob-side entry retaining

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Abstract. This study proposes a “large and small structure” concept of cutting cantilever based on the technical principle of gob-side entry retaining in a non-pillar. A mechanical structure model of the “small structure” concept of cutting cantilever is established by analyzing the stress transfer mechanism of the overlying strata in the gob-side entry. The calculation formula of the roof sinking is derived. The deformation law of the surrounding rock and the roof subsidence characteristics in the small structure are studied using a numerical analysis method. Moreover, the surface displacement curve is obtained by combination with the field measurement. The results show that the cutting structural plane generated by pre-splitting blasting effectively changes the stress transfer between the roof of the gob-side entry and the working face, which is beneficial to the rapid formation of the large structure with a self-stabilization bearing. The deformation of the surrounding rock of a “small structure” roadway is significantly controlled and combined with the rigid support system comprising constant-resistance and large-deformation anchor cables, gangue prevention structures, and a pier-beam unit. The gangues in the goaf interact with the large and small structures formed by the surrounding rock of the gob-side entry retaining, thereby forming a synergistic support structure for effectively increasing roadway stability.

1. Introduction

The problems of low resource recovery rate and serious waste caused by the traditional coal pillar mining method have become increasingly prominent with the decrease of coal resources. Correspondingly, in the coal mining process, how to realize “energy savings and emission reduction”
and implement human survival and sustainable development strategies have become an urgent task [1]. The development of a gob-side entry retaining technology has successfully solved the problem of resource waste and stress concentration caused by coal pillars between working faces. By canceling the coal pillar, the gob-side entry retaining technology realizes continuous mining without a coal pillar, reduces the roadway drivage ratio, alleviates the conflict of mining replacement, optimizes the layout of development and mining, cancels the stress concentration in the upper and lower areas of the coal pillar, and realizes a Y-type ventilation. This technology is one of the green, safe, and efficient mining technologies that can be used to preserve coal resources [2].

The traditional gob-side entry retaining technology often uses the filling body beside roadway as the main support way of the gob-side entry. However, some scholars have found that the filling body beside the roadway is in the stress concentration area during the first roadway and the second mining process [3]. Furthermore, the migration law of the overlying strata of the roadway states that the filling body beside roadway not only should have enough rigidity, but also adapt to roof deformation. When the filling body is too large, the phenomenon of “hard-supported multiple loads” easily appears [4], making the filling body undergo excessively high loads that exceed its carrying capacity and plastic failure. The excessive deformation of the filling body will make the roof of the gob-side entry unstable and lose its function. The high cost of the filling material and the incompleteness of the project connection have restricted the rapid development of the gob-side entry retaining technology [4–5]. Therefore, some scholars have put forward the theory of “roof cutting short-wall beam” and formed the non-pillar mining technology with gob-side entry retaining [6]. Through its three core technologies, the non-pillar mining technology with gob-side entry retaining has changed and optimized the classic law of the confining pressure distribution, formed a new work layout, and effectively solved the problems left by the traditional gob-side entry retaining. It also has a broad application prospect [7–14].

Through advanced pre-splitting blasting, the non-pillar mining technology with the gob-side entry retaining makes the roadway roof form a slit structure surface at the side of the goaf, thereby blocking the stress transmission path of the overlying strata. At the same time, with the mining of the working face, the gangue rib formed by the collapsed gangue will undergo the collapse–compact–stabilization process. The gangue rib interacts with the surrounding rock of the roadway to form a cooperative support structure, which redistributes the stress of the surrounding rock of the roadway [15]. This basic principle leads to a significant difference between the surrounding rock deformation characteristics of non-pillar mining with gob-side entry retaining and the surrounding rock deformation of the roadside filling gob-side entry retaining. Therefore, it is greatly significant to study the deformation characteristics of the surrounding rock under the condition of non-pillar mining with gob-side entry retaining for the maintenance of the gob-side entry and the continuous development of the technology. At present, the research of domestic and foreign scholars on the non-pillar mining technology with gob-side entry retaining mainly focuses on the exploration of technical principles, the study of supporting parameters, and the support of gangue walls in the goaf. For example, He Manchao established the mechanical model of the “surrounding rock structure–roadside support body” of the gob-side entry under different roof positions by analyzing the migration characteristics of the overlying strata of the gob-side entry, deduced the calculation formula of the roadside support
resistance, and put forward the idea of a dynamic pressure yield of the gob-side entry retaining by cutting roof and pressure and overall strengthening of the surrounding rock control [16]. Gao Yubing comprehensively used field measurement, numerical simulation, and laboratory tests to systematically study the deformation and the stress mechanism of the gangue rib in thick coal seams. Cutting roof, mechanical, and numerical models were also developed to explore the dynamic impact behaviors of the gangue body for different mining height effects. A multi-level control approach of the dynamic pressure anti-scour, slow pressure yield, and constant-pressure stable control was also proposed based on the obtained results [17]. Meanwhile, Sun Xiaoming used mechanical modeling and numerical simulation to analyze and study the key parameters of roof cutting [18]. Guo Zhibiao analyzed the main failure characteristics of deformation and soft rock roadway in a tectonic stress area through a site engineering investigation. The deformation, failure mechanism, and main control factors of the surrounding rock under no support or ordinary bolt net support and the relationship between the surrounding rock and the supporting body were also studied through a numerical simulation [19].

However, the influence of the non-pillar mining technology with the gob-side entry retaining on “large structure” and “small structure” of the surrounding rock and the deformation characteristics of the “small structure” of the surrounding rock under the given deformation condition of the main roof remain unclear [20–21]. This study investigates the influence of the non-pillar mining technology with gob-side entry retaining on the “large structure” and “small structure” of the surrounding rock of the working face through a theoretical analysis and puts forward the concepts of “large structure” and “small structure” of non-pillar mining with gob-side entry retaining. The deformation characteristics of the surrounding rock of “small structure” of non-pillar mining with gob-side entry retaining are studied through mechanical modeling and numerical simulation. In addition, the roadway support scheme for non-pillar mining with gob-side entry retaining is given.

2. “Large structure” and “small structure” roof cutting of short wall of non-pillar mining with gob-side entry retaining

2.1. Technical principle of non-pillar mining with gob-side entry retaining

The non-pillar mining technology with gob-side entry retaining refers to the following: after the formation of the reserved roadway working face system, constant resistance and large-deformation cables are used to reinforce the support in the roadway and the goaf side based on the original support. Before the working face mining, the bilateral cumulative tensile blasting technology is used to pre-split blast the roadway roof along the direction of the gob along the goaf side to form a slit structure surface, thereby cutting off the stress transmission path of the goaf and roadway roofs and enabling them to be have an independent deformation (Figure 1(a)). After the working face mining, the goaf roof gradually collapses along the cutting face under the influences of self-weight and mine pressure. Under the combined action of the temporary-support single hydraulic prop and gangue support in the roadway, the collapsed gangue after three stages of collapse, compaction, and stability formed a gangue wall with a bearing capacity along the roadway direction and a stable cooperative support structure with a temporary support behind the hydraulic prop and the coal gang to jointly support the overlying strata and limit the rotation and subsidence deformation of the main roof. Consequently, the roadway roof is converted from the original long-arm rock beam to a short
cantilever beam, which greatly reduces the cantilever load and its action length. At the same time, the newly formed roadway is in the pressure relief area under the upper stable load-bearing structure, which is conducive to roadway stability. After the roadway is formed, it will also be used as the next working face entry to realize the single-face and -roadway mining mode (Figure 1(b)).

![Diagram](image)

(a) Section

(b) Plan

**Figure 1.** Principle of the gob-side entry retaining formed by roof fracturing

2.2. *Division of the strata structure of non-pillar mining with gob-side entry retaining*

The non-pillar mining technology with gob-side entry retaining uses the bilateral cumulative tensile blasting technology before the working face mining to make the roadway roof form a slit structure surface along the strike of the side of the goaf. In this way, the main roadway and goaf roofs form two independent deformation units. The slit structure surface formation cuts off the stress transmission path of the goaf and roadway roofs and greatly weakens the stable structure of the goaf roof, making it collapse in time under the action of the mining stress and self-weight of the working face to form a structure with a certain bearing capacity as early as possible. The height of the slit structure surface enables the abovementioned process to occur in the goaf roof within the slit height range. The gangue that collapses in the goaf can fill the goaf in time because of the broken expansion effect of the rock. It then gradually becomes compact under the load of the overlying strata and forms a structure with a stable bearing capacity with the overlying key rock blocks that underwent rotation and subsidence. The flexible support system, which combines the active support technology of constant-resistance and large-deformation cables, constant-pressure shrinkable temporary support in the roadway, and sliding
yielding gangue support, forms a dynamic and stable structure under the upper stable bearing structure. The two structures are independent of each other and interact with each other, forming large and small structures of non-pillar mining with gob-side entry retaining different from longwall mining with coal pillars and roadside filling along with the gob-side entry [22].

The large structure of non-pillar mining with gob-side entry retaining refers to the stable bearing structure composed of key rock blocks A, B, and C and the collapsed and filled gangue in the goaf, which can support the load of the overlying soft strata. On the contrary, the small structure of non-pillar mining with gob-side entry retaining refers to the dynamic and stable structure composed of the immediate roof, coal wall, and flexible support system in the roadway under the action of a large structure (Figure 2).

2.3. Deformation calculation of the “small structure” in non-pillar mining with gob-side entry retaining

When key block B in the large structure of non-pillar mining with gob-side entry retaining fully rotates and sinks, a stable masonry beam structure is formed with key blocks A and C under the effective support of the gangue in the goaf. During this time, the small structure bears the biggest load effect brought by the large structure before forming the stable structure. The deformation of the small structure also reaches the maximum. The deformation of the surrounding rock of the small structures under the given deformation conditions of the main roof, which is very important for the layout of the flexible system in the roadway and the selection of structural units, must be studied.

First, the mechanical model of a “small structure” roof subsidence in non-pillar mining with gob-side entry retaining is assumed as follows: 1) key rock block B rotates and sinks at the elastic–plastic junction of solid coal as the rotary axial goaf side; 2) the collapsed gangue can fill the goaf in time and support the key rock blocks; 3) the main roof and floor are regarded as rigid bodies, and the immediate roof and coal rock mass are deformable bodies, which do not consider the bond between various rock layers; 4) the upper boundary of the immediate roof is the given deformation of the main roof; the right boundary is free; and the left boundary is the fixed end; and 5) the two ends of the main roof are supported by the collapsed gangue of the goaf and the immediate roof, and the immediate roof...
bears the support resistance in the roadway and the support force of the solid coal gang. Figure 3 depicts the mechanical model of roof subsidence for the “small structure” of non-pillar mining with gob-side entry retaining established according to Figure 2.

Figure 3. Roof sag mechanical model of the small structure in gob-side entry retaining formed by roof fracturing

The mechanical properties of the coal and rock masses around the gob-side entry greatly influence the deformation of the “small structure” surrounding rock. During long geological structure activities, the coal and the rock mass will form weak surfaces (e.g., bedding and joints). These weak surfaces will expand and evolve under the influence of the mining stress, thereby forming a new damage. Damage mechanics are used to describe the damage constitutive relationship of the coal and rock bodies around the roadway [23], as shown in Eq. (1):

\[ \sigma_s = \varepsilon E (1 - D) = \varepsilon E_s \]  

where, \( \sigma_s \) is the effective stress, MPa; \( E \) is the initial elastic modulus of coal and rock mass, GPa; \( E_s \) is the effective elastic modulus, GPa; and \( D \) is the damage variable indicating the degree of coal and rock mass damage.

The model is treated as a plane strain model according to the calculation formula of the strain energy of material mechanics, as shown in Eq. (2):

\[ w = \int \left( \frac{1}{2} \varepsilon^2 E \right) \, dA \]  

The immediate roof deforms with the given deformation state of the main roof. The strain energy \( W_1 \) stored in the process is calculated using Eq. (3):

\[ W_1 = \int \left[ \frac{1}{2} \left( \tan \theta_1 - \tan \theta_2 \right) \right]^2 E_s \, dA = E_s (x_0 + b)^3 (\tan \theta_1 - \tan \theta_2)^2 / 6h^2 \]  

where, \( W_1 \) is the strain energy stored by the immediate roof; \( \theta_1 \) is the main roof rotation angle, (°); \( W_2 \) is the immediate roof rotation angle, (°); \( h_1 \) is the coal seam mining thickness, m; \( E_s \) is the effective modulus of the immediate roof, GPA; \( x_0 \) is the width of the limit equilibrium zone, that is, the distance from the elastic–plastic junction of the solid coal to the coal gang, m; and \( B \) is the roadway width.
Similarly, the strain energy $W_2$ of the solid coal gang is calculated using Eq. (4):

$$W_2 = \int \left[ \frac{1}{2} \left( \frac{x \tan \theta_2}{h_2} \right)^2 E_m d A = \frac{E_m x_0^3 \tan \theta_2^2}{6h_2^2} \right]$$

where, $W_2$ is the strain energy stored in the solid coal gang; $h_2$ is the fitting height of the immediate roof (i.e., cutting height), m; and $E_m$ is the effective elastic modulus of the solid coal gang, GPa.

With the gradual collapse of the lower rock layer on the side of the goaf, the key rock block on the main roof gradually loses its original balance under the influence of the upper rock layer load and mining stress; the rotation deformation occurs; and a stable masonry rock beam structure with key blocks A and C is finally formed under the support of a densely filled gangue in the goaf. According to the S–R stability theory of the masonry beam structure, a subsidence of key rock block B on the main roof exists.

$$\Delta = h_2 - h_1 (k_p - 1)$$

The following formula can be obtained from the geometric relationship:

$$\tan \theta_1 = \frac{\Delta}{l} = \frac{h_2 - h_1 (k_p - 1)}{l}$$

Let us assume that the coal and rock mass are undamaged elastic materials, and the mining depth of the working face is far greater than the mining thickness of the coal seam and the thickness of the immediate roof. Therefore, the stresses on the immediate roof and the coal and rock mass tend to be equal under the neglect of the gravity effect of the immediate roof (Eq. (7)).

$$\frac{(x_0 + b)(\tan \theta_1 - \tan \theta_2)E_S}{h_1} = \frac{x_0 \tan \theta_2 E_m}{h_2}$$

The geometric relationship shows that under the given deformation conditions of the “large structure” of non-pillar mining with gob-side entry retaining, the roof subsidence of “small structure” is denoted by $S$.

$$S = (x_0 + b) \tan \theta_2$$

By substituting Eqs. (6) and (7) into Eq. (8), we can obtain Eq. (9) by calculating the roof subsidence of the “small structure” in non-pillar mining with gob-side entry retaining.

$$S = \left( \frac{(x_0 + b)^2 E_S h_2 [h_2 - h_1 (k_p - 1)]}{[x_0 E_m h_1 + (x_0 + b) E_S h_2]l} \right)$$

When adopting the traditional longwall fully mechanized mining technology under the same mechanical model and conditions, the cantilever length formed by the roadway roof of the “small structure” correspondingly increased after the working face mining because the roof was not cut. In Figure 3, we assumed that the increased cantilever length is the red part, in which the cantilever length will correspondingly become $x_0 + A + B$. Equation (9) shows that the roof subsidence of the “small structure” was positively related to the cantilever length, illustrating the following relationship:

$$S_1 < S_2$$

where, $S_1$ is the roof subsidence of the “small structure” slit measurement of non-pillar mining with
gob-side entry retaining, and \( S_2 \) is the roof subsidence of the “small structure” in the side of the goaf of the traditional longwall mining technology without roof cutting.

3. Numerical simulation of the deformation of the “small structure” surrounding rock in non-pillar mining with gob-side entry retaining

3.1. Project overview

The test face was the 6302 face of Baoshan Coal Mine of the Inner Mongolia Yitai Group. The coal seam was six coal. The coal seam thickness was 1.5–1.6 m. The average thickness was 1.56 m. The dip angle was 1°–3°. The working face depth was approximately 53.5–73.7 m. The strike length of the working face was 1007 m. The inclination length was 200 m. The length of the designed gob-side entry retaining was 913 m. Adopt full seam one passing mining and toward long-arm backward comprehensive mechanized coal mining. The test roadway was 6302 main haulage roadway, the roadway section was rectangular, with a roadway height of 2.45 m and a roadway width of 5 m. The immediate roof of the coal seam comprised 3.78-m-thick fine-grained sandstone. The main roof was mainly composed of 23.2-m-thick sandy mudstone. The immediate bottom was 3-m-thick sandy mudstone. Figure 4 shows the stratum histogram.

**Figure 4.** Bore histogram of B20

3.2. Numerical model

Considering the actual engineering conditions and a simplified calculation and aiming at the production of the geological conditions of the main haulage roadway in the 6302 working face of the Baoshan Coal Mine, we used FLAC3D numerical simulation software to establish the calculation model. A Mohr–Coulomb model was also selected as the constitutive model (size: length \( \times \) width \( \times \) height = 300 m \( \times \) 200 m \( \times \) 85 m). The excavation size of the simulation roadway was 5 m \( \times \) 200 m \( \times \) 2.45 m, while that of the working face was 200 m \( \times \) 200 m \( \times \) 1.6 m. The roadway depth was 80 m, digging along the coal seam roof. The roadway roof comprised 3.78-m-thick fine-grained sandstone,
23.2-m-thick sandy mudstone, and 13.92-m-thick fine-grained sandstone from bottom to top. Meanwhile, the roadway bottom was composed of 3.0-m-thick sandy mudstone and 5-m-thick medium-grained sandstone from top to bottom.

**Table 1. Strata mechanical parameters of the model**

| Name of strata          | Thickness (m) | Bulk (10^9 Pa) | Shear (10^9 Pa) | Friction (°) | Tension (10^6 Pa) | Density (10^3 kg/m^3) | Cohesion (10^6 Pa) |
|-------------------------|---------------|----------------|-----------------|-------------|-------------------|------------------------|-------------------|
| Fine-grained sandstone  | 13.92         | 16             | 17              | 36          | 5.9               | 2.5                    | 5.6               |
| Sandy mudstone          | 23.2          | 10             | 9               | 31          | 3.3               | 2.1                    | 1.6               |
| Fine-grained sandstone  | 3.78          | 13             | 15              | 38          | 4.9               | 2.4                    | 5.4               |
| #6 coal                 | 1.6           | 1              | 2               | 30          | 0.6               | 1.4                    | 1.1               |
| Sandy mudstone          | 3             | 10             | 9               | 31          | 3.3               | 2.1                    | 1.6               |
| Medium-grained sandstone| 5             | 11             | 12              | 33          | 4.9               | 2.4                    | 3.5               |

The left and right boundaries of the model limited the x-direction displacement, while the front and back boundaries limited the y-direction displacement. The applied horizontal compressive stress varied with depth. The lower boundary limited the z-direction displacement, whereas the upper boundary applied a uniform self-weight stress. Table 1 presents the specific rock mechanical parameters of the model. Figure 5 illustrates the calculation model.

**Figure 5. Calculation model.**

3.3. Deformation simulation analysis of the “small structure” surrounding rock of non-pillar mining with gob-side entry retaining

The deformation law of the small-structure surrounding rock of non-pillar mining with gob-side entry retaining was analyzed using FLAC3D to establish the calculation model. Numerical calculations were then performed for models with and without cutting. Figures 6 and 7 show the calculation results.
After the working face excavation, an obvious stress concentration zone was observed inside the solid coal side of the gob-side entry retaining under the “without cutting” condition (Figure 6(a)). The maximum vertical stress was 17.8 MPa. The stress concentration zone was close to the roadway side (i.e., at a distance of approximately 3.0 m), which easily caused adverse phenomena, such as coal wall spalling. A high vertical stress was also observed within 15 m above the roadway and the working face. The maximum vertical stress was approximately 10 MPa. This caused the deformation of the surrounding rock of the roadway, which was not conducive to the roadway stability. After the working face excavation, the internal stress concentration zone of the solid coal gangue of the 15° slit roadway was found to be far away from the roadway side at a distance of approximately 6 m (Figure 6(b)). The maximum vertical stress was 10.9 MPa. A relatively obvious pressure relief area existed within 15 m above the roadway, with the maximum vertical stress of approximately 8 MPa.
China Rock 2020

IOP Conf. Series: Earth and Environmental Science 570 (2020) 052007
doi:10.1088/1755-1315/570/5/052007

11

Figure 7. Vertical displacement cloud pictures of the roadway without and with 15° cutting

The roadway roof was greatly affected by the collapse of the strata above the goaf (Figure 7(a)). The deformation was larger on the goaf side and smaller on the solid coal side, with the maximum displacement of approximately 2500 mm. The cutting seam effectively cut off the stress transmission between the roadway and the goaf roof, thereby effectively controlling the roadway roof deformation (Figure 7(b)). The maximum vertical displacement observed on the goaf side was 300 mm.

In conclusion, the stress concentration zone with pre-splitting cutting was transferred to the deep part of the solid coal. The maximum values of the vertical stress and displacement were also significantly reduced. This proved that the pre-splitting cutting can cut the stress transmission path of the roof off the goaf and the roadway roof and enable them to have an independent deformation, thereby forming a relatively independent stable structure under the cooperative action of the flexible support system, which is different from the traditional mining method. The bilateral cumulative tensile blasting technology formed a weak rock surface in the goaf side in advance. Hence, the overlying strata can fracture and collapse quickly along the slit structure surface under the action of load and mining stress, successfully unloading the huge surrounding rock pressure and reducing the roadway roof subsidence.
4. Small-structure surrounding rock support system in non-pillar mining with gob-side entry retaining

The traditional support method of the gob-side entry has two disadvantages: 1) a certain amount of deformation cannot be given to the roadway roof and overlying strata, which causes the failure of the roadway support when it exceeds the stress limit under a strong mining pressure; and 2) the strength of the roadway support is usually increased blindly to avoid causing the first failure, but strengthening the roadway support will not unload its surrounding pressure, and the effect of “strong-support multiple loads” can easily be observed. When the support is withdrawn in the later period, the roof will suddenly sag under the action of a residual load, which will cause roadway instability.

Different from the previously reported support methods, the 110 method of non-pillar mining with gob-side entry retaining uses the bilateral cumulative tensile blasting technology to perform the pre-split cutting, realizes the first pressure relief of the surrounding rock of the roadway, and locally forms a relatively independent small structure. A rigid support system is then used for structure support. The system comprises three parts, namely the active support with constant resistance and large-deformation cables, the temporary support with constant pressure and a retractable roadway, and the support with sliding and yielding gangue. Combined with the surrounding rock deformation characteristics, the rigid support system undergoes the two following stages: given force and given deformation. In the given force stage, when converting the overlying strata from equilibrium to limit equilibrium, the load transmitted in the support system does not reach its working resistance; the stress in the system will significantly increase; and the deformation will be smaller. When the overlying strata transition from limit equilibrium to instability, the surrounding rock pressure of the roadway will continue to increase. The given deformation stage is reached when the working resistance of the support system is reached. Accordingly, the small structure is fully unloaded for the second time by an appropriate deformation. The roof is also supported by constant working resistance.

4.1. Active support with constant-resistance and large-deformation cables

A constant-resistance and large-deformation cable is mainly composed of cone disk, nut, pallet, constant-resistance device, connecting sleeve, and lock body. The constant resistance, which can be extended by sliding at the tail, is its core component. Relying on a constant-resistance device, the constant-resistance and large-deformation cable can both restrain the deformation using a high constant-resistance value and absorb the surrounding rock deformation performance by extension.

The supporting action process of the constant-resistance and large-deformation cable is different from that of the ordinary anchor cable because of the function of the constant-resistance device. The process can be divided into three stages according to the load–deformation relationship of the constant-resistance and large-deformation cable. The first stage is the given load stage, in which the load constant-resistance value of the overlying strata of the roadway is determined; the constant-resistance device does not enter the working state; and the anchor cable stress continues to rise, albeit with a relatively small deformation. In this stage, the pre-stressed cable provides support force to the surrounding rock of the roadway and enhances the surrounding rock strength. The second stage is the given deformation stage, in which the load of the overlying strata continues to transfer downward with the continuous working face excavation. The pre-stressed cable enters the plastic yield stage when the surrounding rock load exceeds the cable’s elastic limit load. During this time, the
constant-resistance device starts to enter the working state. The constant-resistance device begins to slide and extend when the load continues to increase to a constant-resistance value. Given the amount of subsiding roadway roof deformation, the stress of the surrounding rock of the roadway is unloaded to reduce the stress accumulation strength of the surrounding rock in the roadway. The third stage is the stable stage. The surrounding rock of the roadway reaches the stable stage when the surrounding rock pressure and the supporting force reach a dynamic balance. During this time, the constant-resistance and large-deformation cable reaches the maximum deformation. The gap between the maximum deformation of the constant-resistance cable and the maximum design allowable for the deformation of the constant-resistance cable is taken as a safety reserve that acts as a buffer in the occurrence of adverse geological disasters, such as large deformations of impact and of soft rock.

![Figure 8](image_url)

**Figure 8.** Support principle of the constant-resistance and large-deformation anchor cable

4.2. *Temporary support with constant pressure and retractability*

With the continuous working face mining under the influence of the mining pressure and action, the overlying strata began to gradually lose stability, began to rotate and subside along with the elastic-plastic interface, and transmitted the pressure through the lower strata. When the gangue in the goaf was not filled and compacted and cannot effectively support key rock block B to form a stable supporting structure (i.e., the large structure of non-pillar mining with gob-side entry retaining cannot support the load of the overlying strata and will pass the pressure directly to the surrounding rock of the “small structure” through the immediate roof), the stress of the “small structure” surrounding rock began to significantly increase, and the surrounding rock of the roadway gradually entered the plastic zone and deformed. In this stage, effective support measures must be taken to promote the surrounding rock-stable stage transition. With the dynamic process of the gob gangue from stability to collapse to compaction to stability, the “small structure” experienced different stages from limit stability to instability to dynamic stability to stability. The 110 method puts forward the idea of a control strategy of the rock roof with “zonal support, dynamic support, and flexible support.” Accordingly, the gob-side cut roadway is divided into the advance support zone, support zone behind the hydraulic support, and stable zone of the roadway to adapt to the change rule of the roof pressure and subsidence deformation of the gob-side cut roadway.
One of the main components of the temporary support system with constant pressure and retractability was composed of a single hydraulic prop, a roof-flexible cushion block, and other combinations (Figure 9). If necessary, column boots can be added at the bottom of the single hydraulic prop to prevent ground drilling caused by excessive pressure. The single hydraulic prop is characterized by fast resistance increase, high rigidity, constant pressure, and shrinkage, which provide enough roof cutting resistance in time, make the goaf roof collapse along the pre-splitting cutting surface, produce a certain amount of shrinkage deformation, release the rock layer energy, and avoid damage to the single hydraulic prop due to the excessive roof load.

![Figure 9. Constant pressure and shrink temporary support system](image)

4.3. Support with sliding and yielding gangue
Filling and compacting the gangue in the goaf after the working face mining takes a long time. Under the influence of the load of the overlying strata or mining, the roof at the goaf side will subside more than that at the solid coal side. Therefore, the gangue retaining device should be able to give a certain amount of deformation to the roof to prevent the “pressure bar instability” phenomenon. The potential energy is converted into impact kinetic energy during the gangue collapse in the goaf, thereby producing a lateral impact on the gangue support and making it deform laterally. In other words, the gangue retaining device of non-pillar mining with gob-side entry retaining should not only have a strong resistance to lateral deformation, it should also be able to slide in the longitudinal direction to adapt to the deformation of the “small structure” surrounding rock.

The sliding and shifting gangue support system (Figure 10(a)) composed of a single hydraulic prop, a sliding gangue retaining device, and a steel mesh is proposed herein based on the abovementioned deformation characteristics of the “small structure” surrounding rock in non-pillar mining with gob-side entry retaining. The sliding gangue retaining device (Figure 10(b)) is the core component of the system mainly composed of two U-shaped steel superimposed and connected by a clamp. By adjusting the clamp pretension, the extrusion pressure between the two U-shaped steel sections was adjusted to set the friction force between the two sections, such that it not only has sufficient longitudinal support force, but also can produce longitudinal sliding and yield when the roof is heavily pressed. This ensures that the gangue retaining device will not be bent laterally, improves the reuse
rate of the gangue retaining device, and greatly reduces the support cost.

(a) Schematic diagram of the support system of the sliding and yielding gangue retaining

(b) Sliding-type mutual gangue retaining device

Figure 10. Slip and abdicating gangue prevention system

5. Engineering application
A “bolt + metal mesh” combined support was used in the primary support form of the main haulage roadway in the 6302 working face of the Baoshan Coal Mine. Accordingly, an Ø18 mm × 1800 mm left-hand non-longitudinal rebar threaded steel bolt was used for the bolt. The inter-row spacing between 0 m and 470 m from the open-off cut was 1100 mm × 1000 mm, while that between 470 m and the stoping line was 1000 mm × 1000 mm. A 120 × 120 × 8 mm steel plate tray and a CK2370 resin roll were used for the roadway. The roof was hung with 4600 × 1100 mm welded cold-drawn metal mesh.

5.1. “Small structure” support parameter design of non-pillar mining with gob-side entry retaining
Finally, the following support design parameters were determined (Figure 11) according to the geological conditions of the 6302 working face of the Baoshan Coal Mine and the deformation characteristics of the “small structure” surrounding rock of non-pillar mining with gob-side entry retaining:
1) The active support system of the constant-resistance and large-deformation cable comprises the
following: anchor cable diameter: 21.8 mm; length: 7300 mm; constant-resistance device length: 500 mm; outer diameter: 79 mm; maximum allowable deformation: 300 mm; constant-resistance value: 35 t; pre-tightening force: not less than 28 T; cutting seam-side constant-resistance and large-deformation cable row spacing: 1000 mm, 500 mm from the roadway side; and adjacent constant-resistance and large-deformation cable connected with a W-type steel belt. A row of constant-resistance and large-deformation cables is arranged along the middle line of the roadway with a row spacing of 3000 mm.

2) The temporary support system with constant pressure and retractability comprises the following components: an advance support zone with 30 m distance from the working face and two single hydraulic props in each row (i.e., 1000 mm away from the roadway side and 1000 mm away from the row); a support zone behind the hydraulic support, in which a one-beam and three-column support are adopted 150 m behind the hydraulic support, and has a column spacing of 1000 mm and a row spacing of 1000 mm; and a stable roadway zone, in which the gangue in the goaf is tightly filled, and the supporting single hydraulic prop in the roadway can be gradually withdrawn after the surrounding rock of the roadway stabilizes.

3) The supporting system with the sliding and yielding gangue comprises the following component: support form of the single hydraulic prop + retractable U-shaped steel + reinforced mesh. The single hydraulic prop and the U-shaped steel are both located at the cutting seam side with a spacing of 500 mm.

(a) Design of the temporary support parameters
5.2. Displacement monitoring and analysis of “small structure” surface of non-pillar mining with gob-side entry retaining

5.2.1 Stress of the constant-resistance and large-deformation cable

The support scheme of the flexible support system of non-pillar mining with gob-side entry retaining was formulated and implemented in the 6102 working face of Baoshan Coal Mine according to the abovementioned research and analysis of the deformation law of the small-structure surrounding rock in non-pillar mining with gob-side entry retaining. The change of the roof support force of the remaining roadway during the working face progress and the roof cutting can reflect the roof cutting process and the roof subsidence law; thus, a remote online Pu monitoring system was adopted to monitor the force of the anchor cable of the retaining roadway roof. The influence range of the dynamic pressure ahead of the mining face was approximately 20 m and 12–20 m in advance. The stress growth of the anchor cable was relatively slow because of the small influence of the stress driven in advance. From 12 m ahead to approximately 15 m behind the hydraulic support, the gangue in the goaf did not collapse or collapsed insufficiently because of the working face mining. Lacking effective support for the upper stratum, the anchor cable stress dramatically increased, reaching the maximum value of 349 KN. The gangue in the goaf started to fully collapse with the continuous working face mining. Moreover, with the breaking of the main roof, the anchor cable stress started to gradually decrease and reached the minimum value of 232 KN. When the gangue in the goaf continued to collapse and gradually started to be compacted, the roof in the goaf came into contact with the roadway roof under the action of lateral stress, squeezing each other to produce a large positive stress. The anchor cable stress began to gradually increase because of the friction force brought by the collapse of the roof in the goaf. Accordingly, the lateral force on the roadway roof began to reach a stable value when the gangue in the goaf basically collapsed and compacted. No continuous sinking deformation occurred, and the anchor cable stress began to stabilize, reaching 292 kN.
Figure 12. Monitoring curve of the anchor cable force

2) Surface displacement of the surrounding rock of the roadway

During the stoping and retaining roadway of the 6302 working face, a comprehensive measuring station was arranged at a 50 m interval in the main haulage roadway; a manual cross-measuring point was arranged at a 10 m interval within 50 m from the open-off cut; and a manual measuring point was arranged at a 20 m interval from 50 m to 200 m. The deformation of the surrounding rock of the roadway was monitored with the manual cross-measuring point, which mainly recorded the roof subsidence, two-side displacement, and floor heave. Figure 13 depicts the surface displacement monitoring curve of the S5 measuring point (TC845 m).

(a) Monitoring curve of the convergence between the roof and the floor
The surface displacement monitoring curve of the S5 measuring point showed that under the influence of the advance support pressure, the roadway started to deform when it was approximately 30 m away from the working face. Within the 0–60 m range behind the working face, which was the dynamic pressure influence area, the roadway violently deformed. Meanwhile, within the 60–120 m range, which belongs to the dynamic pressure stable area, the roadway deformation tended to be gentle with the gradual collapse and compaction of the roof at the side of the goaf. At 120 m behind the working face, the gangue in the goaf collapsed and compacted, providing sufficient support reaction force for the overlying strata and forming a stable “large structure” of non-pillar mining with gob-side entry retaining with the upper main roof and key blocks. This reduces the surrounding rock deformation of the lower small structure and belongs to the deformation stable area. The roof of non-pillar mining with gob-side entry retaining had an approach of 296 mm, of which the roof subsidence was 180 mm, and the bottom heave was 116 mm. The two-side displacement was 135 mm, of which the auxiliary side was 27 mm, and the positive side was 108 mm.
The surface displacement monitoring curve of the S7 measuring point showed that the roadway began to deform when the advance working face was 22 m. Within the 0–60-m range behind the working face, which is the intense deformation area, the roadway violently deformed. On the contrary, within the 60–128-m range, which belongs to the stable deformation area, the roadway gently deformed. At 120 m behind the working face, which belongs to the stable deformation area, the daily average deformation of the roadway was ≤1 mm. The final roof subsidence was 155 mm. The bottom heave was 91 mm. The positive side was 91 mm. Lastly, the auxiliary side was 49 mm.

The analysis of the displacement monitoring curves of S5 and S7 roadways showed that the floor heave of the small-structure surrounding rock of non-pillar mining with gob-side entry retaining in the Baoshan Coal Mine was less than the approach of the roof. This result indicates that the slit structure surface formed by pre-splitting blasting before the working face mining can fully depressurize the surrounding rock pressure of the roadway. Moreover, the timely collapse and filling of the gangue in the goaf can also reduce the downward transfer stress of the overlying strata. The positive-side shrinkage was much larger than that of the auxiliary side, denoting that the stress concentration area on the side of the solid coal was far away from the roadway surface, and the stress intensity was small because of the active pressure relief of the small structure of non-pillar mining with gob-side entry retaining by the cutting seam. The shrinkage of the two sides was mainly caused by the impact load from the collapse of the gangue in the goaf and the broken expansion effect of the rock, which had a large lateral force on the sliding yield gangue retaining system and led to its production of a certain amount of force toward the roadway overall slip.

5.3. Effect of leaving roadway onsite

After the working face mining, the goaf roof was cut down along the slit structure surface to form the roadway side under the action of the constant-deformation cable active support system, constant-pressure shrinkable temporary support system, and sliding yield gangue retaining support system. The roof gradually stabilized after 60 m of mining and reached a stable area after 120 m. During the cutting of roof and retaining of roadway period, the roadway height was maintained within 2.2–2.4 m. The roadway width was maintained within 4.7–4.9 m. Moreover, the shrinkage rate of the roadway section was controlled at approximately 8%. The surrounding rock of the roadway had good integrity and was basically stable, ensuring safe working face mining and meeting the site.
requirements. Figure 15 depicts the field application effect.

![Effect of the roadway side formation](image)

(a) Effect of the roadway side formation

![Effect of secondary mining retaining roadway](image)

(b) Effect of secondary mining retaining roadway

**Figure 15. Site application effect**

6. Conclusions

The following conclusions were obtained in this study:

1. The “large structure” and “small structure” concept of non-pillar mining with gob-side entry retaining was put forward herein according to the principle of non-pillar mining with gob-side entry retaining and the component unit of stable structure formation. The interaction of “big structure” and “small structure” of non-pillar mining with gob-side entry retaining led to a stable structure.

2. We established a mechanical model of the “small structure” of non-pillar mining with gob-side entry retaining. The calculation formula of the roadway roof subsidence was deduced based on the knowledge of strain energy in rock damage and material mechanics.

3. We used FLAC3D numerical simulation software to analyze the influence of the bilateral cumulative tensile blasting technology on the roadway roof subsidence law. Compared with the traditional coal mining technology, the non-pillar mining technology with gob-side entry retaining greatly reduced the deformation of the surrounding rock of the roadway, which is conducive to the roadway service for the next working face.

4. A rigid support system was used herein to stably support the small structure. After the working face mining, the goaf roof was rapidly cut down along the pre-split structural surface to form the roadway side under the roof cutting effect of the support system. As a result, the surrounding rock of the
roadway obtained good integrity, thereby ensuring safe working face mining and meeting site use requirements.

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**Acknowledgement**

The project was funded by China Postdoctoral Science Foundation (2020T130702).