Numerical simulation study of the support system by gob-side entry retaining by roof cutting

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Abstract. Gob-side entry retaining by roof cutting (GERRC) is an innovative, long-wall mining method that has been widely used in China as a new mining revolution. However, current research on the influence of this technology on the support system remains limited. To understand the response of each supporting structure after cutting the roof, this study uses the cable element and beam element built in the finite difference software FLAC 3D to simulate the bolt, anchor cable, steel beam, and single hydraulic props based on the engineering geological conditions of the Lvtang Coal Mine in Guizhou Province, China. Then, the force and displacement changes of each supporting structure between the GERRC and traditional coal pillar mining are compared and analyzed. Simulation results reveal that during the process of conventional mining, the force and deformation of anchor cable behind the working face is relatively large; furthermore, even yield and breaking of the cable occurs. Meanwhile, the serious deformation of a single hydraulic prop occurs, which affects the normal use of the roadway. When the GERRC is adopted, the force of each supporting structure is reduced by 17.6% on average and the deformation is not obvious. Moreover, using the GERRC decreases the stress of the supporting and reduces the displacement of solid coal in the roadway by 33.3%. Finally, the concentration degree of stress becomes lower, and the environment of retaining roadway is more optimized.

1. Introduction
The stress environment in deep mining is complex and changeable, and the deformations of roadway surroundings are more obvious. Moreover, compared with the traditional coal mining method, the activities of the roadway surroundings are made more intense by means of the gob-side entry retaining (GER). Thus, controlling the deformations of the roadway surroundings entails the implementation of efficient support measures. With the aim of overcoming the deformations of the roadway surrounding rock, the current main single support methods in China include bolt support[1-3], cable anchor support, section steel support[4], steel tube concrete support[5-6], and U-steel confined concrete support, among others[7], among others. Furthermore, there are two or more kinds of support forms in coordination with each other, which are called coupling support forms[8-9]. These two kinds of support forms can solve the problem of large deformation of roadways surrounding rocks in middle and shallow coal seams and most deep coal seams with stable geological conditions. However, for soft rock roadways with large buried depth and weak and broken surrounding rock, conventional support methods often break because of excessive elongation, and the support capacity is decreased or even completely lost. Thus, there is an urgent need to change the existing support concept to develop new support forms.
Ordinary bolts and cables provide typical rigid support. According to the concepts of “energy absorption” and “pressure concession,” many scholars have developed new types of anchors, such as the D bolt, Yielding-Lok bolt, Garford bolt, energy-absorbing bolt, and Roofex bolt[10]. However, these new types of anchor cables are still made of traditional materials. Although their support effect is better than that of ordinary anchor cables, the diameters of the rods are smaller and the deformation also becomes smaller when subjected to tension. Thus, these new cables still cannot move in coordination with the surrounding rock. Based on this problem, a researcher developed constant resistance and large deformation cable (CRLDC) according to the characteristics of negative Poisson material. The maximum elongation of the CRLDC is 1000 mm, which has the advantages of constant resistance, high pretension, and large elongation, among others[11].

Sun et al. carried out dynamic tensile experiments on the CRLDC and analyzed it from the aspects of bolt elongation, support resistance, energy absorption, and diameter deformation. Their results reveal that the CRLDC has the characteristics of high support resistance, energy absorption, and long elongation, which can adapt to downhole nonlinear large deformation[12]. Li and He conducted dynamic impact experiments on the CRLDC, and analyzed the mechanical characteristics of force and deformation at different impact rates. Their experimental results indicate that the CRLDC can maintain constant resistance by producing structural deformations to absorb impact energy, thus demonstrating its dynamic anti-impact performance[13]. Meanwhile, Tao studied the response characteristics of the CRLDC under static and dynamic loads through indoor experiments and investigated the energy absorption laws of the CRLDC by numerical simulation for the first time. The experimental results are highly consistent with the numerical simulation results. Another study reported that the CRLDC has a great energy absorption capacity[14].

The coupling support system formed by the CRLDC combined with contractible U-shaped steel, I-beam, bolt, and steel mesh has shown great performance in field application, which can fully meet the needs of large deformation of roadways surrounding rock. At present, the GERRC, including the coupling support system, has been successfully applied in over 500 mines across China. This has resulted in huge economic and social benefits and helped promote the development of the coal industry.

2. The technical principle of the GERRC
The schematic of coal pillar mining is shown in Figure 1(a). The roadway of this working face will collapse after the mining of the current face is completed. The roadway of the next face will be retained due to the bearing capacity of the coal pillar to the roof. On the one hand, the roadway roof will form a “long cantilever beam” state. The roof collapse of the goaf is a process occurring from the bottom strata to the top strata with evident time and space effect, so the gangue cannot fill the goaf in time, thus providing space for the further subsidence of the overlying strata. On the other hand, the rotation and subsidence of the overlying strata will squeeze the long cantilever beam, which would cause distinct deformations of the roadway surroundings in the next working face.

Figure 1(b) shows the schematic of the GERRC. First, the CRLDC is used to reinforce the entry roof, after which the bilateral gathered tensile explosion technology (BGTET) is carried out on one side of the entry goaf according to the designed angle, height, and distance between blast holes. The entry roof will form a slit surface along the axial direction of the entry, thus taking the shape of a “short cantilever beam” state, and the fracturing roof will fill the goaf sufficiently. At the same time, due to the action of the cutting seam, the goaf roof near the retained entry is the first to collapse. The gangue can contact the goaf roof in time and support it, which can mitigate the rotation and subsidence of the overlying strata, which in turn, reduces the deformations of the entry surroundings. The gangue will be prevented from entering into the roadway under the action of blocking gangue by the contractible U-shaped steel beside the roadway, and the retained roadway can continue to serve for the next working face.
3. The movement structure model of the surrounding rock by the GERRC

The roof of the remaining roadway will go through four processes, as shown in Figure 2. The state of the roadway roof affected by working face mining and the pre-splitting of the roof is analyzed in detail by establishing the structural model of each process. Meanwhile, analyzing the movement of the overlying rock is of great significance for maintaining the roadway stability and improving road support.

As shown in Figure 2(a), the CRLDC starts to be arranged at least 100 m in front of the face based on the original support of the roadway. At this time, the overlying strata are in a stable state, and the surrounding rock of the roadway is not affected by the advanced abutment pressure of the working face. The entry roof is in a fixed state due to the support of solid coal on both sides of the face.
Figure 2(b) indicates that the splitting face is formed after conducting the BGTET along the axial direction of the entry, which can cut off the stress transfer between the goaf roof and the roadway roof. The entry roof is not affected by the advanced abutment pressure when it is far away from the working face. Moreover, although the BGTET is carried out on the roof, the surrounding rock of the roadway is almost undeformed due to the excellent energy accumulation effect of the energy collecting device. When the entry roof is close to the working face and is affected by the advanced abutment pressure, the abutment pressure in front of the working face will not be transferred to the solid coal of the roadway, thus ensuring that the roadway is in the pressure relief area. Therefore, the pressure of the entry roof will decrease, and the deformations of the roadway surroundings will become small. The roadway roof can be regarded as simple support at the one side (goaf side) and fixed support at the other end (solid coal side).

Figure 2(c) shows that the immediate roof begins to collapse, and the cutting seam can effectively increase the breaking degree of the goaf roof when the working face pushes through the cutting seam zone. Thus, the gangue in the area is affected by the cutting seam connecting the main roof rapidly. The collapsed gangue will effectively support the overlying strata and further prevent the main roof from rotating and sinking. This is the direct reason why the roof pressure of the remained roadway is reduced by the GERRC. The gangue collapsed in the goaf will have low bulk characteristics if the entry roof is not influenced by the cutting seam, and as a result, the gangue cannot fill the goaf in time. Hence, the break and subsidence of the overlying strata will produce a voussoir beam structure, and the load of the overlying strata will be transferred to other hinged beams through this structure. As the immediate roof has been splitting, the roadway roof is under a cantilever beam state; thus, the roadway roof can be regarded as a cantilever beam at one end (goaf side) and a fixed support at the other end (solid coal side).

As shown in Figure 2(d), the surrounding rock of the roadway is in a stable state and the movement of the overlying strata becomes smooth when the cutting seam is behind the working face for a certain distance. Moreover, the stope voids are filled by caved-in rock materials, which are compacted by the overlying strata. As the cutting seam blocks the connection between the goaf roof and the roadway roof, the load of the overlying strata can hardly be transferred to the solid coal, and most of it is concentrated in the goaf, which is not affected by the cutting seam. The roadway roof is strongly supported by the CRLDC, and the surrounding rock is stable as a whole. Hence, the temporary support in the roadway can be removed periodically. The roadway roof can be regarded as a simple support at one end (gangue support in the goaf) and a fixed support at the other end (solid coal side).

4. Engineering geology conditions
The Lvting Coal Mine is located in Bijie area, Guizhou Province, China. The S204 working face in the No. 6 coal seam is located in the second mining area in the south. This working face is at the +1800 level, and the underground elevation is +1900. The ground consists of uneven mountainous area, with no rivers, villages, and buildings. The adjacent working faces are S205 and S203. The strike length of the S204 working face in the No. 6 coal seam is 796 m on the head entry and 772 m on the tail entry, with an average of 784 m. The mining dip length is 115 m. The inclination angle of the coal seam varies from 3° to 9°, with an average of 6°. Moreover, the thickness of coal seam ranges from 0.9 to 7.55 m, with an average of 3.5 m.

The average buried depth of the S204 mining panel is 210 m. Figure 3 shows the geological drilling of the panel. The roof strata above the S204 face mainly consists of muddy siltstone and silty mudstone, and the floor stratum consists of silty mudstone, muddy siltstone, and coal. As shown in the stratigraphic column, the lithology of the roof and the coal seam changes greatly.
Figure 3. Generalized stratigraphic column.

5. Support form
Bolts and metal meshes as well as anchor cables are adopted for the support method of the entry roof. Here the two ribs of the entry are only supported by bolts and metal meshes. The interval between the bolts (diameter: 20 mm, length: 2200 mm) is 800 mm × 800 mm. The exposed length of the bolts is 30–50 mm, and all of them are anchored at the end. The square-shaped tray is made of steel materials and has the following length × width specification: 120 mm × 120 mm.

The interval between the anchor cables (diameter: 15.24 mm, length: 6000 mm) is 1600 mm × 1600 mm, and two columns of cables are arranged in each row. The effective length of the anchor cables ranges from 5650–5750 mm. The tray is made of rail, and a round hole with a diameter not less than 16 mm is drilled on it. The metal mesh consists of a steel bar with a diameter of 4 mm; its length × width specification is 1800 mm × 1000 mm, and the size of the longitude and weft grid is 100 mm × 100 mm. The schematic of the original support is shown in Figure 4.

Figure 4. Schematic of the original support.

The section diagram of the GERRC is shown in Figure 5. Two rows of the CRLDC (diameter: 21.6 mm, length: 10000 mm) are used to reinforce the roadway roof. The first row of the CRLDC is 500–800 mm away from the coal rib, with the interval of 1000 mm. The second row is located in the
middle of the entry with the interval of 1600 mm. Both rows of the CRLDC are perpendicular to the entry roof. The length of the cutting line is 8000 mm, and the angle is 15°, which can lead to the smooth collapse of the goab roof.

![Figure 5. Section diagram of the GERRC.](image)

The side views of the U-steel units and hydraulic props are shown in Figures 6 and 7, respectively. The contractible U-steel units are used near the gangue rib to prevent the gangue from running into the entry. The mining height of the working face reaches 3.5 m; thus, the U-steel units are composed of two pieces of 2-m short U-shaped steel rods, which overlap each other. Two fasteners are used to fix the overlapping part of the U-steel units. The U-steel units should be inserted into the floor for 200 mm, thus preventing them from skewing under the action of the lateral thrust of the gangue.

![Figure 6. Layout of the U-type steels.](image)

The metal meshes are also used to prevent small pieces of gangue from running into the entry. The U-shaped steel is thicker in the middle than in other parts, which makes it difficult to have transverse deformation to restrain the subsequent deformation of the gangue rib. When the entry roof continues to sink, vertical stress will be applied to the U-steel units. If the stress is greater than the friction force between the two short U-shaped steels, then the U-steel units will slip relatively, thereby releasing a certain amount of deformation energy.
6. Simulation of the reinforcement support with the CRLDC

6.1. Model building
The model is divided into eight layers, and the size (length × width × height) is 160 m × 160 m × 50 m. The Mohr–Coulomb criterion is used in the model. Constraints are imposed on the surrounding and bottom surfaces in order to restrict its movement. To simulate the weight of the overlying rock layer, a stress of 5.25 MPa is applied on the upper surface. A three-dimensional (3D) numerical model is established according to the geological situations of the S204 coalface in the Lvtang Coal Mine, as shown in Figure 8. The mechanical parameters of each rock mass are given in Table 1.

![Figure 7. Layout of the hydraulic props.](image)

![Figure 8. Three-dimensional numerical model of the S204 coal face.](image)

| Lithology          | Density /kg/m³ | Tension /MPa | Cohesion /MPa | Friction /° | Bulk /GPa | Shear /GPa |
|--------------------|----------------|--------------|---------------|-------------|-----------|------------|
| Coal               | 1550           | 2.35         | 1.45          | 25.20       | 1.31      | 1.44       |
| Sandy siltstone    | 2240           | 1.43         | 3.07          | 32.00       | 6.47      | 4.33       |
| Silty mudstone     | 2450           | 3.52         | 2.18          | 35.10       | 4.16      | 7.40       |
Next, the numerical simulation analysis of the bolts and anchor cable support in the tail entry is carried out. The cable element is added to simulate the anchor cables and bolts according to the actual working conditions. Meanwhile, the beam element is used to simulate the single hydraulic props. Then, the displacement of the entry surroundings and the force of the support structure with or without the CDLDC in the tail entry is compared and analyzed. The lines in Figures 9 and 10 represent the different support forms of the support system and are designed according to the actual engineering situations.

6.2. Support simulation model

The difficulty in the simulation of the support system lies in the simulation of the CRLDC. This is because the cable element in the FLAC\textsuperscript{3D} is an ideal elastic-plastic model. Moreover, its working resistance first reaches the maximum value in the way of linear growth, i.e., it enters the plastic state and remains stable at the maximum working resistance, as shown in Figure 11.

This situation is in accordance with the actual working conditions of the anchor cable when the force of the cable element does not reach the yield strength. Once the force of the cable element exceeds the yield strength, the working resistance decreases or may even be lost under actual conditions. However, the cable element in FLAC\textsuperscript{3D} cannot reflect this characteristic. Therefore, the constitutive model of cable element in FLAC\textsuperscript{3D} must be improved by recomposing fish language to realize the simulation of the CRLDC. As shown in Figure 12, under the premise of constant working resistance, the working resistance of the CRLDC will reduce to 0 after a certain amount of deformation.
The yield strength and axial tensile deformation of cable element are first set once the constitutive model of the CRLDC is established. Then, the specific and detailed values need to scale and discount the actual constant resistance force and deformation amount of the CRLDC. Thus, the anchorage end parameters (gr_coh, gr_fric, gr_k, and gr_per) of the element become higher than the yield strength. Finally, the anchorage end and the free end of the element are set to be in rigid contact with the surrounding rock, thus allowing the cable element to move with the surrounding rock. During the numerical simulation, when the axial force applied on the cable element reaches the constant resistance value, the cable produces axial tensile deformation. When the deformation exceeds the limit value, it means that the cable failed.

6.3. Simulation results

Figures 13 and 14 show the displacement and force of the original supporting structure, respectively. As can be seen, the deformation and force of the anchor cable near the goaf side of the tail entry is larger than that of the anchor cable in the middle of the tail entry under the condition of original support in the tail entry. Moreover, the maximum deformation of the anchor cable near the goaf is 370 mm, whereas the maximum deformation of the anchor cable in the middle of the entry is 300 mm, which is less than 70 mm compared with that near the goaf. The maximum force of the anchor cable near the goaf is 14.5 MPa, and the maximum force of the anchor cable in the middle of the entry is 11.5 MPa, which is 3 MPa less than that in the adjacent goaf.

At the same time, the force and shrinkage of the single hydraulic props near the goaf are also larger than those in the middle entry or near the solid coal. The deformation and force of the roof bolt along the entry are larger than that near the solid coal, whereas the maximum deformation of the bolt near the solid coal is about 150 mm, which is consistent with the actual situation on the spot. In summary, the subsidence of the roof along the entry is larger under the condition of original support, while the surrounding rock of the solid coal rib is in good condition.
Figures 15 and 16 show the force and displacement of the support structure strengthened by the CRLDC. The simulation results indicate that the stress and deformation of ordinary anchor cable can be greatly reduced with the addition of the CRLDC. Moreover, the maximum deformation of the ordinary anchor cable is 255 mm, which is 120 mm less than that without the CRLDC, indicating that the effect of the CRLDC on the suspension of immediate roof is significant. The force and deformation of the anchor cable near the goaf is still larger than that of the anchor cable in the middle of the entry, and the force and deformation of the roof bolt is still larger than that of bolt near the solid coal. Moreover, the force and deformation of the single hydraulic props near the goaf is also larger than that of the single hydraulic props near the solid coal and in the middle entry.
As can be seen in Figure 17, the shoulder angle of the roadway is obviously deformed under the original support. Moreover, the displacement of the solid coal is large, with the maximum displacement recorded at 300 mm. As can be seen in Figure 18, the vertical displacement of the middle entry roof is about 300 mm after the increase of the CRLDC. Meanwhile, the vertical displacement in the goaf side of the roadway roof is about 500 mm, which becomes obviously larger than other positions of the entry. Compared with the simulation results of the vertical displacement under the situation of original support structure, the vertical displacements of the goaf side of the roadway roof and the solid coal are reduced by ~250–500 and 100 mm, respectively. The displacement of solid coal in the roadway is reduced by 33.3%. At the same time, the phenomenon of bottom heave has been alleviated.
We monitored the deformations of the entry surroundings and recorded the relationship between the displacement of the monitoring point and the distance of the working face in detail. Figure 19 presents the curve of the relationship between the distance of the working face and the deformation of the surrounding rock. The changes of the roadway surroundings mainly go through three stages: sharp deformation zone, slow deformation zone, and stable zone. The deformations of the roadway surroundings increase rapidly within the range of 0–40 m behind the working face. Simultaneously, the slope of the curve becomes increasingly bigger, indicating that the deformation rate of the entry surroundings is gradually accelerated. Within this range, the deformation of floor heave is obviously greater than that of the roof subsidence, and the displacement of the solid coal is also larger than that of the goaf rib. The gangue is gradually compacted by the overlying strata when the entry roof fully collapses, and the deformation and deformation rate of the roadway surroundings slows down. When the observation station is 80 m behind the working face, the roadway surroundings become increasingly stable.
7. Conclusion
(1) During the process of conventional mining, the force and deformation of the anchor cable behind the working face are relatively large, even leading to yield and breaking of the cable. Meanwhile, the serious deformation of the single hydraulic props affects the normal use of the roadway. When the GERRC is adopted, the force of each supporting structure is reduced by 17.6% on average, and the deformation is not obvious. Moreover, using the GERRC decreases the stress of the supporting structure and reduces the displacement of solid coal in the roadway by 33.3%.
(2) When roof reinforcement is carried out along the remaining entry, the arrangement of the CRLDC near the goaf must be encrypted, and the arrangement of the CRLDC at other locations must comprehensively consider the existing supporting structure. On the basis of cutting down the cost, the stability of the roof is maximized.
(3) The numerical simulation results reveal that the use of the CRLDC can play an active role in strengthening the roof support effect and reducing the roof subsidence. Furthermore, the CRLDC near the goaf has a greater stress than the cable on the middle of the entry.

Acknowledgments
I would like to thank Professor Guo for his careful guidance on my thesis. He has given me many reasonable Suggestions on theoretical analysis and numerical simulation, which has greatly improved my writing skills.

References
[1] Yang J, He M C and Cao C 2019 Tunn. Space Technol. 90 309
[2] Gao Y B, Wang Y J, Yang J, Zhang X Y and He M C 2019 Tunn. Space Technol. 90 99-118
[3] Wang Q, He M C, Yang J, Gao H K, Jiang B and Yu H C 2018 Int. J. RockMech. Min. Sci. 110 1-8
[4] Guo Z B, Zhang L, Ma Z B, Zhong F X, Yu J C and Wang S M 2019 Shock Vib. 2019 143413
[5] Zhen E Z, Gao Y B, Wang Y J and Wang S M 2019 Adv. Civ. Eng. 2019 5267240
[6] Guo Z B, Wang Q, Li Z H, He M C, Ma Z B, Zhong F X and Hu J 2019 Int. J. Low Carbon Technol. 14 23-35
[7] Hu J Z, He M C, Wang J, Ma Z M, Wang Y J and Zhang X Y 2019 Energies 12 934
[8] Qian M G 1981 The Equilibrium Condition of Overlying Strata in Stope (Beijing: J. China Min. Univ.) pp 34-43.
[9] Song Z Q 1979 The Basic Law of Overlying Strata Movement in Stope (Shandong: J. Shandong Min. Univ.) pp 64-77.
[10] Zhu Z Q, Song Y, Liu Y X, Chen M B and Hua Y F 1982 The Behavior RegularityLaw and Application of Abutment Pressure in Stope (Shandong: J. Shandong Min. Univ.) pp 1-25.
[11] He M C, Gong W L, Wang J, Qi P, Tao Z G, Du S and Peng YY 2014 Int. J. RockMech. Min. Sci. 07 29-42.
[12] Sun X M, Wang D, Wang C, Liu X, Zhang B and Liu Z Q 2014 Chinese Journal of Rock Mechanics and Engineering 33 1765-71.
[13] Li C, He M C and Gong W L 2016 Journal of China Coal Society 41 1393-99.
[14] Tao Z G, Zhu Z, Han W S, Zhu C, Liu W F, Zheng X H, Yin X and He M C 2018 Advances in Mechanical Engineering 10 1-13.