Factors that affect the stability of roads around rocks

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\section*{ABSTRACT}
The control method of deformation of large sections of soft rock formations in coal mines is a major problem in mining practice. Taking Wangzhuang Coal Mine in Shanxi Province, China, for example, the support method of large sections of soft rock formations was studied to control the deformation of the top and bottom plates and two gangs, and to obtain the damage of the surrounding rocks at different depths through drilling imaging. In addition, the displacement, plastic area and stress field distribution patterns of surrounding rocks are obtained by simulating in FLAC3D. Coupling support for broken, plastic and elastic zones is achieved using bolts, grout anchors, and long anchor cables. The bottom of the road is effectively controlled by floor grout and concrete reverse arches. The results show that under the combination of anchorage and grout, the fault depth and degree of the surrounding rocks are less than the original support method, which can effectively reduce the subsidence of the roof and the deformation of the two gangs. It is important to note that anchorage cable set support can effectively reduce shear fault areas in floor and two gang plastic areas, and reduce the weight of the pavement floor. This study provides a technical reference for the support of large sections of soft rock roadways in coal mines.

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\section*{1. Introduction}
The location and section size of the road are based on the occurrence conditions of the coal seams and mining techniques. However, roofs and formations always belong to soft rock formations, and the failure of soft rock roads differs greatly from other rock formations, such as high crustal stress and large deformation of surrounding rocks (Guo et al. 2015: Xie et al. 2015: Yang et al. 2017). It can be summed up as loose, scattered, soft and weak (Lin 2011). In the production process, due to the dynamic disturbance of production and the physical characteristics of rock, soft rock road has a large deformation. At the same
time, due to lack of or insufficient support technology, the roadway is unable to maintain production requirements, and continued large deformations have seriously affected the normal production of coal mines (Tan et al. 2017; Fu et al. 2020).

Depending on the carrying characteristics and support principles of the surrounding rocks (Jeremic 1985; Dong et al. 1994; Mark and Balczak 2000; Anagnostou and Cantieni 2007, Barla et al. 2010, the support methods for coal mine laneways can be divided into four categories: providing support directly on the rock surface: providing support from the rock surface to the Deep support: Changing the mechanical properties of surrounding rocks: decompression, combined support technology (Cantieni 2011; Tan et al. 2017) When the roof’s formation is hard or difficult to lower, anchoring cables or U-shaped steel (Zhang et al. 2014; Wang et al. 2018) is generally used to support road preparation. Due to the long service life of the development road, anchoring spray or anchoring is commonly used in the development road to achieve the service life. Anchor net spray is used to support surrounding rocks, thereby reducing the deformation of surrounding rocks (Yao 2009; Pang and Wang 2012), which does not affect the normal use of the road. However, when excavating roads in soft rock formations, the traditional support method can not achieve the purpose of support and reinforcement. In the study of the support method of Soft Rock Road (He 1991), the scholars adopted corresponding support methods according to the differences between the characteristics of rock science and coal seam burial in different regions, such as the combined support of “bolt cable-mesh projectiles and shells” (Yang et al. 2017): constant resistance large deformed bolts (Guo et al. 2015): Floor mud and grout anchor cable (Wu et al. 2018): Concrete-filled steel pipe support (CSTS) (Huang et al. 2018) and pipe umbrella roof support method (Schumacher and Gold 2013). These support methods achieve the goal of effectively controlling the deformation of surrounding rocks through different new joint supports, and also control the deformation of soft rock formations. FLAC3D (Itasca Consulting Group Co., Ltd. 2005; Yang et al. 2019) numerical simulation software is used to simulate the support effects of different theoretical models (Zhang and Xie 2012; Yang et al. 2019). At the same time, the failure mode and characteristics of the supporting material (Zhang et al. 2013; Li et al. 2016; Song et al. 2017, Li et al. 2018) are simulated to improve the support properties of the support material and better control the deformation and damage of the surrounding rocks.

Digging large sections of roadways in rock formations or coal seams will not only affect the internal stress distribution of rock formations, but also cause local stress concentration, increase the fault area of plastic areas, increase the difficulty of roadway support (mountain, etc. 2012; Tao et al. 2018) to solve the support of large sections of roadways. Methodological problems, in view of different geological conditions, put forward a large perfusion anchor, spray anchor network support technology and full-face grille concrete (Meng, etc. 2013), channel beam and anchor rope combination, steel belt combination anchor rope (Yang, 2009) and other geological conditions of the comprehensive support measures. However, support is not valid due to large deformation of the road during support. Therefore, a support method combining active support and passive support is proposed, which greatly improves the carrying capacity of deep rocks and maintains the long-term stability of the road (Zhan et al. 2011).
However, digging large sections of the road in soft rock formations will face two serious problems, which will make it more difficult to support the road. One is a soft rock formation that will have a lot of deformation, and the other is the majority of the space that is provided for the deformation of the formation. In addition, numerical simulation software FLAC is based on the deformation characteristics of the original support technology and the physical properties of the surrounding rocks. Three-dimensional used to simulate the displacement, distribution of plastic areas, and stress field on roads around rocks. The coupling support of broken area, plastic area and elastic belt is realized, and the purpose of controlling the deformation of surrounding rocks is achieved.

2. Road geological conditions

Wangzhuang Coal Mine is located in the city of Changzhi, Shanxi Province, China, 10 kilometers from Changzhi City, the coal mine’s traffic location can be seen in Figure 1. The coal mining depth is about 300 meters and the inclination is 3 to 7 degrees. The main ore layer is the No. 3 coal seam, which belongs to anth anthostite and is 6 meters thick. The geological structure belongs to the simple structure. The roof and floor rock layer of coal seam No. 3 are mainly composed of thin coal seam,
mudstone, sandstone, fine sandstone, mudstone, fine sandstone, limestone and medium grain sandstone, with relatively low strength. The cross-section area of the equipment roadway is 96 m², which is larger than other roadways, and the width is 9.8 m and the height is 10.81 m. The total length of the transshipment roadway is 562 m and the equipment roadway is 99 m. The roadway is in the middle of several roadways that interact with each other, whose main function is used to place the mining devices (shown in Figure 2). The roadway was excavated by using blast, however, its section was so large that was very difficult to construct. And the other three adjacent roadways include a large one, the distance between roadways is 24 m. The cross-section area of the roadway is 70 m², 74 m² and 80 m², respectively. There are multiple roadway intersections near the equipment roadway, and the stress at the intersection is more concentrated.

Near the equipment roadway, there are 5 points to measure the ground stress by using the hydraulic fracturing method, these measuring stations were located at 50 m, 150 m, 280 m, 400 m, and 530 m in the adjacent ventilated roadway (shown in Figure 2). The measurement results show that the maximum principal stress of the surrounding rock is horizontal, next is vertical stress, and the ratio of the horizontal stress and the
vertical stress is about 0.87 ~ 1.66. In this study, the direction of roadway is N41°E, the direction of maximum horizontal stress is about 10.8° ~ 64.7° North by East, and there are three measuring points, which angle between the maximum horizontal stress and the roadway direction is about 20° ~ 30°. The fifth measuring point is the furthest one to the equipment roadway, which is 622 m, the angle between the maximum horizontal stress and the direction along the roadway is about 33.2°.

Rock burst has occurred many times. The soft rock stratum was thicker among the surrounding rock in the roadway, and the lithology of the roadway surrounding rock is weak and the stability is poor. According to roadway roof disclosure, the immediate roof is sandy mudstone, and in turn is mudstone, fine sandstone, mudstone, fine sandstone, coal seam, etc. The floor is sandy mudstone and followed by limestone, coal line, mudstone, etc. Uniaxial compression tests are carried out for the roof and floor strata of No. 3 coal seam by using the RMT-150C, the thickness of mudstone and silty mudstone in roadway surrounding rock is larger, and the strength of mudstone is weaker. Under the influence of tunneling at large section roadways and intersections, stress concentration makes mudstone deformation and destruction easily. The rock strength, roadway location in surrounding rock, and lithology of roadway floor and roof are shown in Figure 3, it should be noted that the (a) ~ (d) around the roadway in Figure 3 are the location of (a) ~ (d) in Figure 4. Also, the bolts around the roadway in Figure 3 reflect the original support structure and correspond to the failure characteristics in Figure 4.

3. Original support parameters and failure characteristics

3.1. The failure modes of roadway

In the initial period of roadway support, bolts (nets) are used to support the roof. The specifications of bolts and anchor cables are $\Phi 21.6 \times 2500$ mm and $\Phi 21.6 \times 8300$ mm, they are arranged respectively, and the row spacing is $700 \times 700$ mm and $1600 \times 1600$ mm. The support methods of bolts and anchor cables are shown in Figure 3. After roadway construction, about 2 months, the roof, floor,
and two gangs of roadway were severely deformed. The convergence between the two gangs of roadway is above 1000 mm, the amount of roof subsidence is more than 300 mm, and the floor distension is 400 ~ 800 mm, which seriously affects the stability of the roadway surrounding rock. To satisfy the needs of the later work, the roadway needs to be repaired, and the project is delayed so that causing economic losses.

Combined with the results of roadway field observations (shown in Figure 4) and drilling imaging of surrounding rock (shown in Figure 5), and based on the failure reason and pattern of roadway surrounding rock, the failure modes are divided into five categories, including loose failure, tensile failure, shear failure, rock-burst failure, and expansion deformation failure. The causes of failure are as follows: Under the pressure influence of surrounding rock and blasting construction, the surrounding rock appears loosening and slips along the weak plane of bedding and joint (Figure 4a). Also, because of the large span of the roadway section, the spray layer on the surface of the roadway was significantly tension failure under the pressure of the roof. The stretch failure zone has emerged and extends along the roadway in the roadway vault and two spandrels (Figure 4b and c), the interior structure of the surrounding rock undergoes shear failure under triaxial stress (Figure 4d); Rock-burst sometimes occurs in the brittle rock of roof under concentrated stress caused by the excavation of large cross-section roadway, and expansion deformation and failure of mudstone rock occurred in the local water-leaching area.

The size of the crushing zone and the plastic zone is an important basis for the roadway to design support, and their size is determined by drilling imaging, theoretical and numerical calculation. Therefore, the drilling imaging was used to obtain the deformation and damage of the surrounding rock at different depths (show in Figure 5). It can be seen that within the range of 0 ~ 2.5 m, the surrounding rocks are fractured and fail; within 2.5 ~ 8.0 m, the surrounding rock fractures gradually decrease; and the surrounding rock is relatively intact beyond 8.0 m.

3.2. Analysis of the failure reason

The main causes of deformation and failure in the roadway are large sections, high stress, low strength of surrounding rock, and irrational support method.

3.2.1. Large section

The cross-section size directly affects the stability of the roadway. To study the failure depth of surrounding rock in different sections, numerical simulation was carried out
on a section of 14.28 m², 32.13 m², 57.12 m², 89.25 m² respectively by using FLAC 3D software, to obtain the distribution laws of the displacement, plastic zone and stress field of surrounding rock in different roadway cross-section size (shown in Figure 6), there is a kind of rock in the numerical models to ensure one variable, and the location of roadway was excluded. The parameters of the surrounding rock can be seen in Table 1. According to the simulation results (shown in Table 2 and Figure 7), with an increasing area of roadway cross-section, the plastic zone radius of the roof and both gangs increased significantly. Besides, after the cross-section exceeds 60 m², the plastic zone radius of the floor increased slowly, which changing trend is consistent with the roadway displacement. When the width and length of the roadway are 10 m, the plastic zone radius of the roof, two gangs, and the floor are 8 ~ 10 m.

3.2.2. High crustal stress and low strength of surrounding rock
The stress of surrounding rock is closely related to crustal stress and the disturbance stress caused by excavation. The buried depth of the roadway is 440 m, the initial vertical stress of the stratum, where the roadway is located, reaches 8 ~ 10 MPa, and the maximum horizontal stress reaches 10 ~ 12 MPa. The maximum principal stress of the surrounding rock reaches 20 ~ 25 MPa because of the large cross-section size of the roadway and the larger stress concentration factor. There are many soft strata such as mudstone, sandy mudstone, and so on. Also, the strength of the surrounding rock is smaller due to the influence of the weak structural surface, like rock layers, joints, cracks, and so on. The secondary disturbance stress caused by the excavation of the ultra-large section roadway causes larger deformation and destruction of the soft surrounding rock.

3.2.3. Support parameters
The selection of support methods and parameters has a great influence on roadway stability. The original support scheme has the following problems: The bolts with 2.5 m length are anchored in the crush area, the anchoring force and working resistance

Figure 5. Drilling imaging results with different depth of the first point.
are smaller, and the anchor bolting effect cannot be fully exerted. Moreover, the pre-
stress of the high-strength bolt with Φ21.6 mm is 350 N m, the pre-tightening force
is lower, so it is not matched with the yield strength of 500 MPa, which weakens the
function that active and timely support of the high-strength bolt and affects the exer-
tion of its working resistance, the row spacing of bolts, grouting anchors and anchors
are 700 mm, 1600 mm, 1600 mm respectively. Also, the distance between the rows is not matched, the density of support is not uniform, and the local stress concentration causes the surrounding rock or spray layer cracking.

Table 1. Mechanical parameters of the surrounding rock in the numerical model.

| Material | Bulk modulus/GPa | Elastic modulus/GPa | Internal friction angle/° | Cohesive force/MPa | Tensile strength/MPa | Thickness/m |
|----------|-----------------|---------------------|--------------------------|-------------------|---------------------|-----------|
| Rock     | 3.6             | 3.5                 | 24.5                     | 18.5              | 36.0                | 66        |

Table 2. The sizes of roadway and destruction depth of surrounding rock.

| Roadway width/m | Vertical wall height/m | Cross-section area/m² | Destruction depth/m |
|-----------------|------------------------|-----------------------|---------------------|
|                 |                        |                       | Roof | Gangs | Floor |
| 4.0             | 4.0                    | 14.28                 | 3.5 | 3.0   | 4.0   |
| 6.0             | 6.0                    | 32.13                 | 5.5 | 4.5   | 6.0   |
| 8.0             | 8.0                    | 57.12                 | 6.0 | 6.5   | 8.0   |
| 10.0            | 10.0                   | 89.25                 | 8.5 | 10.0  | 9.5   |

Figure 6. Simulation results of different roadway cross-section sizes. (a) 14.28 m²; (b) 32.13 m²; (c) 57.12 m²; (d) 89.25 m².

Figure 7. The influence of roadway cross-section on deformation and failure.
Because of its large cross-section size, molding after blasting is poor, the surface of surrounding rock is uneven and easy to form stress concentration. The construction quality of bolts (net) and cable is poor, which affects the full play of the overall support effect.

Based on crustal stress, rock mechanical properties, and support conditions, the plastic zone radius of the roadway surrounding rock can be calculated by the limit equilibrium theory (Hou 2013).

\[ R_p = R_0 \left[ \frac{(P - c \cdot \cot \varphi)(1 - \sin \varphi)}{P_i + c \cdot \cot \varphi} \right]^{1 - \sin \varphi \over 2 \sin \varphi} \]  

(1)

where \( P \) is original rock stress, 8.0 MPa; \( R_0 \) is the radius of the roadway, 5.0 m; \( P_i \) is support resistance, 0.2 MPa; \( c \) is adhesive property, 1.0 MPa; \( \varphi \) is the angle of internal friction, 30°. So the plastic zone radius is 7.9 m.

The development characteristics of cracks in surrounding rock were obtained by drilling imaging (shown in Figure 5), combined with the results of the theoretical calculation (Eq.1) and numerical simulation, it can be deduced the approximate scope of crush zone, plastic zone, and elastic zone of roadway surrounding rock, which range is as follows: 0 ～ 2.5 m is crushed zone, 2.5 m ～ 8.0 m is the plastic zone, and the depth beyond 8.0 m is the elastic zone (shown in Figure 8). It can be seen from the failure modes, the surface of the roadway has formed tensile failure, and the interior structure of the surrounding rock should shear failure.

Figure 8. The sketch of failure partition support of roadway in the first stage.
4. Subarea coupling support and simulation

4.1. Subarea coupling support of roadway roof and gangs

Based on the stability principle of the roadway surrounding rock, the subarea coupling supporting method was adopted to support the roadway in the "crush zone of $0 \sim 2.5 \text{ m}$, plastic zone of $2.5 \sim 8.0 \text{ m}$, and elastic zone of beyond $8 \text{ m}$". The bolts, grouting anchors cable, and long anchor cable form three load-bearing rings of $0 \sim 3 \text{ m}$, $3 \sim 8 \text{ m}$, and $8 \sim 15 \text{ m}$, together with the inner ring layer pouring (300 mm) and confining pressure, to achieve the petition coupling support between crushing zone, plastic zone, and elastic zone.

4.1.1. Long bolts support bearing stratum ($0 \sim 3 \text{ m}$)

Based on the crushing zone $0 \sim 2.5 \text{ m}$ of equipment roadway, the 3.0 m long bolt was used to support the first layer so that the anchoring end of the bolt was located in the relatively intact rock stratum (plastic zone). With the increasing of anchor length, the compressive stress zone formed by a single bolt is gradually close to the superposition of each other, the effective compressive stress zone between the anchors expands and becomes a whole, and forming a stable bearing structure (shown in Figure 8). Besides, it is necessary to control the deformation of the roadway in time during roadway excavation, improve the initial support stiffness and strength of the supporting system, effectively control the expansion and deformation, maintain the integrality
of surrounding rock, and reduce the decreasing extent of coal and rock strength. The fracture and pore in the broken area of roadway inevitably develop great, the bearing capacity of surrounding rock and anchoring force of anchor bolt are both relatively weakened, the method of low-pressure grouting with the shallow hole is adopted to make the broken area condensed as a whole, and the grouting hole is shown in Figure 9.

At the same time, restrain the radial and transverse deformation of the surrounding rock in the confined anchorage range is the main factor of the bolt in the fractured surrounding rock, which depends on the anchoring length and the reliable anchoring quality of the bolt and surrounding rock. Moreover, grouting could achieve a good anchoring effect within the full length of the bolt, providing a reliable foundation for the anchor bolts, and further ensure the bearing capacity of the inner structure of the roadway.

Combining anchor bolt support with grouting reinforcement to strengthen the surrounding rock of the roadway. And grouting reinforcement makes surrounding rock form a continuous grouting reinforcement circle. Also, the initial anchor force of the anchor body is added to form the reinforcement ring of the bolt in the surrounding rock, and then the first layer support system is formed by metal mesh and shotcrete concrete.

4.1.2. Grouting anchor cable bearing layer (3/C24 8m)
The grouting cable anchor is to support the plastic zone that is formed during the excavation of the roadway. The stratum in the plastic zone has larger deformation but remains integrity, and the 8 m long grouting cable anchor was used in this design. Firstly, the anchoring agent is used to anchoring the anchorage end, then the high pre-tightening force is added, and grouting reinforcement is carried out in the end. The high-pressure grouting is adopted with the grouting depth of 8 m. The strength of the weak surrounding rock is improved, which forms the bearing structure of the second layer (shown in Figure 9). Grouting reinforcements change the deformation characteristics of surrounding rocks. Moreover, grouting in the plastic zone increases the anchoring strength of anchor cables, realizes the transformation from end anchoring to full anchoring, and increases the overall anchoring force.

After grouting reinforcement of the broken surrounding rock, its deformation changes from brittleness to brittle plasticity, and the peak value of the surrounding rock strength after grouting shows a strong plastic characteristic, forming a bearing structure suitable for large deformation. The stability of the surrounding rock strength is maintained in a certain range of deformation, which makes the inner layer structure flexible, and realizes the coordinated deformation of the inner and outer layers of the anchor bolt (cable). The high pre-stressed anchor bolt (cable) timely bearing capacity under the fractured surrounding rock mass and combined with the grouting stratum to improve the bearing capacity of the inner anchor grouting structure. It is possible to establish the connection between the grouting structure (first load layer) and the outer layer structure (second bearing layer) of the inner layer anchor bolt (cable), which make the roadway stable in a wide range and prevent the plastic zone further development of surrounding rock.
The pre-tightening force of the anchor bolt and cable plays a key role in improving the stress state of the roadway surrounding rock. The reasonable support parameters could form a continuous and superimposed effective stress zone in the anchorage zone.

4.1.3. **Long anchor cable support bearing layer (less than 15 m)**

The results of the drilling imaging and numerical simulation show that the plastic zone of the roadway is 8 m. The anchorage end of the anchor cable is anchored in the elastic zone so that the third layer bearing structure is formed by supporting with 15 m long cable, which is shown in Figure 9. The combined arch-rib is larger that formed at the top of the roadway supported by three bearing layers, and the stress acting on the roof can be transferred to the floor. With the increasing thickness of the combined arch, the load concentration degree acting on the floor plate is reduced. Thus the stress and plastic deformation in the floor stratum are weakened and the floor heave is reduced. It also helped to maintain the stability of roadway two gangs and arch roof.

4.1.4. **Masonry crown passive support bearing layer**

After excavating the large section roadway, to control the deformation of surrounding rock, the relevant supporting parameters of the first, the second, and the third load-bearing vehicle are adopted. The reinforced concrete is poured with a thickness of 300 mm; it realizes the isolation of surrounding rock from air and water and has a good sealing effect.

Four kinds of support methods are combined to make it have enough support strength and stiffness, which can effectively control the roof detachment and sliding. On the one hand, the anchoring structure of the anchor bolt and cable with different depths is not destroyed. On the other hand, the anchoring force of the anchor cable can effectively spread to the surrounding rock, control the roof subsidence, and reduce the floor heave. The bolt, the anchor cable (8 m), the long anchor cable (15 m), and the anchor injection form a multi-layer effective combined arch, they are integrated into one body and jointly bearing. These support methods expand the effective bearing range of the supporting structure and improve the integrity and carrying capacity of the support structure. Coupling support in different layers of roadway surrounding rock is a kind of very reliable, effective, economical, and reasonable supporting methods for strengthening the soft rock.

4.2. **Floor heave control**

To prevent the roadway floor heave effectively, the bottom grouting and the concrete reverse arch are selected, and the numerical simulation is used to compare the two schemes. Scheme 1 (shown in Figure 10a) adopts the concrete reverse arch, the maximum arch depth is 2.2 m, and the concrete strength grade is C40. Scheme 2 (shown in Figure 10b) uses the combined support methods of the bottom anchor cable group with grouting, the combined anchor cable is composed of three \( \Phi 21.6 \times 15000 \) mm high strength and low relaxation steel strands, the spacing between the bottom plate
anchor cable groups is 1900 mm \times 2000 mm. Numerical simulation modeling and calculation were carried out based on the two schemes to obtain the control effect of the roadway floor (shown in Figure 10). And the parameters for the support materials are showed in Table 3.

From the simulation, it can be seen that under the support of concrete reverse arch, in the floor surrounding rock, the range of the shear failure area in the plastic zone is reduced from 10 \sim 12 m to 6 \sim 7 m, and the maximum floor heave is reduced from 650 mm to 420 mm without support. Under the condition of floor bolting cable group support, the surrounding rock area where shear failure occurs in the plastic zone of the floor is from 3 m to 4 m away from the bottom plate, the maximum floor heave is 191 mm, and the plastic zone of the two gangs is 1 m less than that of the concrete reverse arch support, which increases the stability of the two gangs. Therefore, the effect of the floor anchor cable group is better than that of concrete reverse support, and the floor anchor cable group support is chosen to control the floor heave in the end.

The approximate calculation model for the broken boundary of the roadway floor is shown in Figure 8, and the depth of roadway floor-breaking can be calculated by (Huang and Hao 2018):

\[
y = \sqrt{\frac{3PW^2 - 12Px^2}{4P + 32(C + \lambda P)}}
\]

where \(P\) is vertical ground stress, MPa; \(W\) is roadway floor width, m; \(C\) is the cohesion strength of roadway floor rock, MPa; \(\lambda\) is lateral pressure coefficient; \(y\) is the breaking depth of roadway floor, m; and \(x\) is the distance from the floor to the center point, m.

The buried depth of the roadway is 450 m, the vertical stress is 10.0 MPa, the width of the roadway is 9.8 m, the surrounding strata of the floor is mainly mudstone and sandstone, and the cohesion of the floor strata is about 5 MPa, and the pressure coefficient is 1.3. When the distance from the floor to center point \(x\) is 0, the maximum breaking depth of the roadway floor is about 2.2 m. Based on the results of the numerical and theoretical calculation, the broken range of the floor is expected to
reach 2.2 m, and the range of the plastic zone reaches 12 m because of the large section of the roadway. So it is necessary to support the floor stratum with an anchor cable group to ensure the roadway’s long-term stability and safety production.

5. Optimization of supporting parameters

5.1. Roof and gangs

5.1.1. Anchor bolt (cable)-mesh

Anchor bolt: There are 37 anchors to support the roadway, and the distance between them is 700 × 700 mm. The method of lengthening anchoring at the end of the resin cartridge is adopted and two anchoring agents were used. The diameter of the drilling hole is 30 mm, the anchor bolt of bottom angle is set down 10°, and other anchors were installed on the surface of the vertical roadway. The exposed length of the anchor bolt is 80～100 mm, the pre-tightening of each bolt is 450 N·m, and the anchoring force is not less than 120 kN.

Anchor cable: there are 17 anchor cables, the length is 8.3 m with 1400 × 1400 mm spacing, 11 anchor cables in the arch with Φ21.6 mm, and 6 anchor cables in gangs with Φ21.6 mm. Three anchoring agents have used for every anchor cable, and the anchoring agents are resin cartridge and the anchorage length is 2000 mm. The anchor bolt of the bottom angle is set down 10°, and other anchors are installed on the surface of the vertical roadway. The exposed length of the anchor cable is less than 300 mm, and the pre-stress of each anchor cable is not less than 200 kN.

Grouting anchor cable: There are 20 grouting anchor cables in the roadway section and the row spacing is 1400 × 1400 mm. Three anchoring agents have been used for every anchor cable, the anchoring agents are resin cartridge and the anchorage length is 2000 mm. The anchor bolt of the bottom angle is set down 10°, and other anchors are installed on the surface of the vertical roadway. The exposed length of the anchor cable is less than 300 mm, and the pre-stress of each anchor cable is not less than 200 kN. Moreover, the mesh is laid by lap connection, the length of the lap is 100 mm, and the 14# tie wire is used for connecting the mesh, the wire and buckle hole are interconnected. The thickness of the sprayed concrete is 150 mm, and the strength grade is C20. The pouring thickness of the roadway with the concrete section is 300 mm, and the strength grade is C40. The partitioned coupling support method of the roadway is shown in Figure 11, and the supporting parameters are shown in Table 4.

5.1.2. Grouting of a shallow and deep hole in the roadway

The roadway reveals that the surrounding rock is sandy mudstone, limestone, and fine sandstone, the rock cracks and the bedding are obvious.
The purpose of grouting is to increase the friction and cohesion of the surrounding rock, to increase the strength of the rock in the broken area and plastic zone of the roadway, and to enhance the stability of broken rock and resist the external force ability. The finer slurry is easy to permeate in the structural plane, and the slurry condenses fill the structural plane, improves the mechanical properties of the weak rock, and increases the resistance of relative movement between the blocks in the rock mass. Using this method could reconnect the broken rock mass as a whole. Because of the large cross-section size of the roadway, the combination of low-pressure shallow hole grouting and high-pressure deep hole grouting is adopted.

Shallow-hole grouting with low-pressure is based on the bolting and shotcreting support for roadway surrounding rock. 2.5 m hole is used to reinforce the broken rock after bolting and shotcreting by low-pressure. Based on the low-pressure shallow hole grouting, high-pressure and deep-hole grouting will form a certain thickness of the reinforcement circle layer, it will expand the reinforcement range, increase the grouting reinforcement effect, and strengthen the low-pressure shallow hole grouting plus solid. The high-pressure and deep-hole grouting improves the bearing capacity of grouting reinforcement significantly.

Shallow-hole grouting with low pressure: 11 holes arrange in the roadway surface, the diameter and depth of grouting hole are 42 mm and 3 m, and the grouting holes are arranged in the shape of an “isosceles triangle”, the row spacing in the two gangs is 3 m × 3 m, the bottom angle hole is inclined 30° downward, the top angle hole is inclined upward 5°, and other drill holes are perpendicular to the roadway surface. The top arch is arranged in a manner with a row spacing of 3 m × 3 m, the arch angle boreholes are inclined up to 15°, and other boreholes are perpendicular to the surface of the roadway. Seamless steel pipes are used for grouting pipes, and the sealing depth is not less than 1 m by using a bore-enveloping implement. The pneumatic single fluid grouting pumps are used to grout with the pressure of 0.5 ~ 1.0 MPa, in which the diffusion radius is about 2 m.

Deep-hole grouting with high pressure: 11 holes arrange in the roadway surface, the diameter of the grouting hole is 42 mm, and the depth of the grouting hole is 8 m, the grouting holes are arranged in the shape of an ‘isosceles triangle’, the row spacing in the two gangs is 3 m × 3 m, the bottom angle hole is inclined 30°
downward, and the top angle hole is inclined upward 5°, and other drill holes are perpendicular to the roadway surface, the top arch is arranged in a manner with a row spacing of 3 m × 3 m, the arch angle boreholes are inclined up to 15°, and other boreholes are perpendicular to the surface of the roadway. Seamless steel pipes are used for grouting pipes, and the sealing depth is 1 m by using a bore-enveloping implement. Also, the grouting pressure of a deep hole is 1.5-2.0 MPa, the reinforcement range is about 10 m, and the grouting diffusion radius is 2 m. The grouting time lags about 7 days after the shallow hole grouting so that the consolidation body of shallow hole grouting can reach a certain strength.

### 5.2. Floor heave

The equipment roadway is used for lifting, assembling, and maintaining hydraulic support supports, and it needs to lay track. The roadway floor heave will seriously affect the

| Materials                  | Support models                      | Strength             | Remarks                                                                 |
|----------------------------|-------------------------------------|----------------------|-------------------------------------------------------------------------|
| Anchor bolt                | Φ21.6 mm × 3000 mm; Left-handed reinforcing bar without longitudinal reinforcement | The ultimate breaking force is 300 kN, the yield force is 225 kN, and the elongation is 20%. |
| Anchor cable               | Φ21.6 mm × 8300 mm; High strength and low relaxation prestressed steel strand | The ultimate tensile force is 400 kN, pre-stressing 200 kN |
| Grouting anchor cable      | Φ21.6 mm × 8300 mm; High strength and low relaxation hollow steel strand | The strength is 1760 MPa, the breaking force is not less than 420 kN, |
| Long anchor cable          | Φ21.6 mm × 15000 mm; High strength and low relaxation prestressed steel strand | The ultimate tensile force is 400 kN, pre-stressing 200 kN |
| Anchor cable group         | Φ21.6 mm × 8300 mm; High strength and low relaxation prestressed Strand | The ultimate tensile force is 1200 kN, pre-stress is 0 kN |
| Grouting material          | GP-3 geopolymers                    | Single liquid grouting, compressive strength above 40 MPa |
| Resin anchoring agent      | K2335 and Z2360                     | Anchorage compressive strength is not less than 60 MPa |

The inner diameter and outer diameter of hollow grouting pipe are 7.5 mm and 10 mm respectively, the grouting pressure is not less than 5.0 MPa, the maximum is 7.0 MPa. The high strength anchor cable tray is used, the length and width are 300 × 300 × 16 mm, the bearing capacity is not less than 40 t. Each anchor cable adopts three anchoring agents, K2335 (1) and Z2360 (2).
normal use of the roadway, and increase maintenance difficulties. Considering the large section of the roadway, it is necessary to support and reinforce the floor of the roadway, so the “anchor cable group with deep-hole grouting” is adopted.

The anchor cable group consists of three high strength and low relaxation steel strands, and the specification is $\Phi21.6 \times 15.0$ m, the specification of steel tray is $400 \times 400 \times 16$ mm, and two groups of anchors are linked by steel beams, which are shown in Figures 12 and 13.

The arrangement of odd rows (1, 3, 5 … ) are as follows: 2 steel beams are used for auxiliary supporting, and the length of the steel beam is 2300 mm, there are 2 holes in each steel beam, the spacing is 1900 mm, and the distance between two steel beams is 1500 mm. Besides, the arrangement of even rows (2, 4, 6 … ) is as follows: 2 steel beams are used for auxiliary supporting. There are 5 holes per row the length of one is 4200 mm with 3 anchor cables, and another one is 2300 mm with 2 anchor cables. Also, the hole spacing is 1900 mm. Firstly, the anchor cable group is placed in the floor holes, then the floor grouting is carried out to make the anchor cable group and the floor rock anchoring better, and finally, the anchor cable is stretched to the prescribed pre-stress after grouting fluid stabilization.

GP-3 grouting material is used for floor grouting, the diameter of the grouting hole is 45 mm, and the depth of the hole is 15 m. Besides, the expected grouting quantity is 75 kg per hole, and the expected grouting volume is 35 t. Also, grouting pressure not less than 3 MPa.

The bottom anchor cable was drilled by the MSQ-100 rig. Each group with three anchor cables is fixed to a tray. The anchoring end is anchored at first, and then the full-length grouting is carried out in construction. After the slurry solidification, the anchor cable is stretched to the prescribed pre-stress.
6. Results and discussion

6.1. The results after supporting

Based on the field observation data from the second measuring point to the seventh, the curves of deformation and time change of surrounding rock (shown in Figure 14) in each station can be divided into three stages, they are rapid deformation stage, slow deformation stage, and stable stage.

The roadway is in the rapid deformation stage after excavation 1~10 d, the maximum convergence value of the two gangs is 47 mm, and the average is 4.7 mm/d; The maximum value of roof subsidence is 30 mm, and the average is 3 mm/d; The maximum value of floor heave is 23 mm, and the average is 2.3 mm/d. The roadway is slowly deformed after excavation 10~75 d, the maximum convergence value of the two gangs is 78 mm with an average of 1.2 mm/d; The maximum value of roof subsidence is 55 mm, and the average is 0.85 mm/d; The maximum floor heave value is 52 mm with an average of 0.8 mm/d. The roadway is in the stable stage after excavation 75~95 d, the deformation of surrounding rock almost does not change in this stage, and the deformation of the roadway is stable.

The surrounding rock of large section roadway has a long time for continuous deformation, and the surrounding rock of normal section roadway almost does not converge after excavation 25~40d, but the deformation of surrounding rock of large section roadway needs about 3 months to reach a stable stage, and the sustained deformation time is long. It can be seen from Figures 15 and 16 that the roadway is relatively stable with the subarea coupling support method. If the support is not reasonable, the accumulated deformation will be larger and larger, and eventually, lead to the destruction of the roadway.

6.2. Discussion

It is difficult to support the continuous deformation of the large section roadway in the soft surrounding rock stratum of Wangzhuang Coal Mine, the drilling core and image are used to determine the lithology and the damage scope, the basic mechanical parameters of surrounding rock were obtained in the laboratory experiment, also, the subarea coupling support is put forward to solve this problem.
The drilling imaging work was carried out before and after the scheme improvement and make comparison and analysis. After using the support method that partitioned coupling control, the failure depth and the degree of the surrounding rock are smaller than that of the original support methods. The failure of shallow surrounding rock is mainly concentrated at 0\,\text{m}^2 to 2\,\text{m}^2, and there is no large shear and tensile failure. Moreover, the anchoring end of the bolt is still in the stable rock strata and plays a very important role in the long-term stability of the roadway surrounding rock. Base on the drilling imaging, there are only a few primary cracks in the range of 2\,\text{m}^2 to 15\,\text{m}^2 of the roadway surrounding rock, and there is no phenomenon of the deep surrounding rock being separated. The results show that the support strength can achieve the need of surrounding rock stability, and the late masonry and grouting reinforcement can ensure the long-term stability of the roadway, and form a relatively complete stable roadway (shown in Figures 15 and 16), the effect of partition support is more obvious.

This study is the intersection of two difficult problems in the coal mine, they are the soft surrounding rock and the large section roadway. The cross-sectional area of roadway in coal mines is generally about 25\,\text{m}^2, and there are no 70–96\,\text{m}^2 large cross-section roadways and less excavation in the soft surrounding rock. This study is an in-depth discussion and analysis in two aspects: the one is that how to control the deformation of the soft surrounding rock effectively, and another one is that the
continuous deformation of large section roadway after excavation. These two serious problems have collided, it would form a new problem in that long-term large deformation and difficult to stable. To solve this serious problem, and based on the stability principle of roadway surrounding rock, the petition coupling support technology is adopted to achieve the petition coupling support between the crushing zone, plastic zone, and elastic zone, which effectively controls the deformation of two gangs, roof, and floor.

7. Conclusions

Based on the failure characteristics and depth of the roadway surrounding rock, this paper analyzes the factors affecting the stability of the roadway surrounding rock, puts forward the supporting methods, and verifies the supporting effect. The following conclusions drawn:

The main reasons for the roadway damage are the large cross-section, high stress, low strength of the surrounding rock, and unreasonable support method. It is concluded that with the increase of roadway section, the plastic zone radius of the roof and two gangs increases greatly, the maximum horizontal principal stress of the roadway reaches $20 \sim 25$ MPa, and there are much soft rock stratum in roadway surrounding rock and many problems in the original support method, it is easy to produce local stress concentration and cause the crack of surrounding rock or gush layer, makes the roadway easy to be deformed and failure.
Numerical simulation and monitoring results show that the loose and broken confining pressure glue can be formed into a whole by using bolt-grouting combined support technology and grouting to fill the cracks of surrounding rock, and the overall strength of surrounding rock can be improved. Also, it can be combined with the anchor net spray support and to form a multi-layer effective composite arch. The bearing capacity of the roadway surrounding rock increases and the surrounding rock is more evenly stressed. Besides, the bearing range and capacity of the supporting structure are expanded, and the surrounding rock deformation and the expansion of the plastic zone are effectively controlled. The anchor-grouting combined support technology is an effective support method to solve the problem of deep high-stress expansion soft rock roadway support.

Compared with the concrete floor arch and the floor anchor cable, the results show that the plastic zone area of the surrounding rock by using the anti-floor arch support method is reduced by 40.91%, and the value of the maximum floor heave is reduced by 35.38%. Besides, the shear failure area in the plastic zone of the surrounding rock by using the anchor cable group is reduced by 68.18%, and the maximum floor heave value is reduced by 70.62%. The plastic zone of the two gangs by using the anchor cable group is $1 \sim 2 \text{m}$ smaller than using the anti-floor arch support method and increases the stability of the two gangs. Anchor cable group support can effectively control the floor heave of the roadway.

The coupling support technology can effectively realize the coupling support for the broken zone, the plastic zone, and the elastic zone. The results of roadway deformation monitoring and numerical simulation show that subarea coupled support can reduce the failure depth and degree of the surrounding rock, and make the anchor end of the anchor bolt (cable) is always located in the stable rock. Meanwhile, the roadway surrounding rock strata separation can be effectively avoided, combined with masonry crown and grouting concreting in the late-stage to ensure the long-term stability of the roadway.

**Statement of performance**

The author did not report a potential conflict of interest.

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**Data availability report**

Data supporting the results of this study may be obtained at the request of the appropriate authors.
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