

Study on Deformation and Failure Mechanism and Control of Surrounding Rock in Super Large Section Roadway

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Abstract

Aiming at the outstanding problems of difficult deformation control and poor stability of surrounding rock in super large section roadway of coal mine, the mechanical mechanism of deformation and failure of surrounding rock in super large section roadway is systematically analyzed, and the typical failure modes such as roof bending settlement, high side wall buckling instability and strong floor heave are expounded. According to its failure characteristics, a comprehensive control technology system with the core of 'step-by-step excavation pressure relief, active coupling support and overall reinforcement of surrounding rock' was constructed, and a collaborative control method of 'advanced pre-support + step-by-step excavation + high pre-stressed anchor net cable spray primary support + reinforced concrete secondary lining' was proposed. The industrial test was carried out in the return air roadway of 8000 working face in Wuyang Coal Mine. The results show that the method can significantly control the deformation of surrounding rock within the allowable range, ensure the long-term effectiveness of support structure and ensure the safety and stability of roadway.

Keywords

Super large cross section ; size effect ; surrounding rock reinforcement.

1. Introduction

In recent years, in order to meet the needs of national energy strategic reserves, China's mineral resources mining has gradually advanced to the deep, and the proportion of super-large cross-section roadways with cross-section area greater than 20m² in underground engineering has increased year by year [1]. Under this trend, the stress environment, deformation law and failure mechanism of surrounding rock of super large section roadway are essentially different from those of conventional section roadway because of its huge excavation span, high span ratio change and complex construction process, so the stability control of surrounding rock is facing unprecedented challenges [2]. Compared with conventional roadways, the stability of surrounding rock in super-large cross-section roadways shows significant characteristics of 'three highs and one difficulty'. First, the degree of stress redistribution is high, and the huge excavation space leads to the geometric growth of the unloading range of surrounding rock. The secondary stress field is extremely complex, and the plastic zone is significantly expanded and irregular in shape. Second, the total amount and rate of deformation are high, and the convergence deformation of surrounding rock is often several times that of conventional roadway, and the deformation duration is long, and the rheological effect is obvious. Third, the risk of structural instability is high, the roof is easy to form a huge 'rock beam' bending and sinking, the high side wall may be buckling instability, and the load on the support system is huge and uneven. Fourth, it is difficult to control the stability. The traditional support theory and technology based on the assumption of small deformation are often no longer applicable. The coupling mechanism between the support structure and the surrounding rock is complex, and the requirements for construction technology and timing are extremely harsh [3].

According to statistics, under complex geological conditions, the incidence of surrounding rock instability accidents during the construction of super-large section roadways is about 40 % - 60 % higher than that of conventional sections, which not only causes huge economic losses, but also seriously threatens the life safety of construction personnel [4]. Scholars at home and abroad have carried out a lot of useful exploration and research on the stability of surrounding rock of large section roadway. At the level of theoretical analysis, through the theory of elastic mechanics, plastic mechanics and damage mechanics, the evolution law of surrounding rock stress field after excavation unloading is preliminarily revealed, and the internal relationship between the range of plastic zone and roadway span and rock mass strength is clarified [5]. In the study of failure modes, various typical forms such as large-scale roof caving, side wall shear slip and floor heave have been identified, and the importance of time-space effect in the deformation process has been emphasized. In terms of control technology, methods such as high prestressed anchor cable support, steel reinforced concrete composite support, and combined use of various support forms have been developed, and certain results have been achieved in practice [6].

However, there are still significant limitations in the existing research. On the one hand, most studies still use or simply extrapolate the mechanical models and conclusions of conventional sections, and lack systematic theoretical characterization and mechanism analysis for the unique ' size effect ' of ultra-large sections (that is, the section size itself becomes an independent dominant factor affecting the stability of surrounding rock) [7]. For the key scientific problems such as the bending settlement effect of the roof rock beam under the super-large span, the buckling instability mechanism of the plate and shell of the high side wall, and the evolution law of the support-surrounding rock interaction under the condition of large deformation, the research is not deep enough. On the other hand, at the level of control technology, the traditional concept of ' one-time excavation and strong support ' is often difficult to adapt to the large deformation of surrounding rock in super-large section roadway, which leads to the problem of excessive strength but mismatched stiffness and premature failure of support [8]. In engineering practice, the common case is that even if the supporting structure with high design load is adopted, there may still be large area cracking of the spray layer, bolt breaking, steel frame buckling and other phenomena, and finally have to carry out costly rework and reinforcement [9]. Therefore, it is urgent to break through the traditional thinking, closely combine the mechanical properties of the super-large section roadway, and develop a corresponding, dynamic, step-by-step, active and coordinated control theory and technical system [10].

In this regard, the internal mechanism of deformation and failure of surrounding rock in super-large section roadway is deeply explored, and its special law different from conventional roadway is clarified. The key influencing factors are systematically analyzed, and the targeted control technology is proposed to ensure the safety and stability of roadway and ensure the safe and efficient mining of mine.

2. Analysis on Deformation and Failure Mechanism of Surrounding Rock of Super Large Section Roadway

2.1. Mechanical mechanism of deformation and failure of surrounding rock in super large section roadway

The essence of super-large cross-section roadway excavation is to form a huge underground space, which makes the unloading range (influence circle) of surrounding rock much larger than that of conventional roadway. Its mechanical response is first manifested as an extremely strong spatial effect. At the moment of excavation, the original in-situ stress state is completely broken. The stress redistribution process is no longer a simple vertical stress transfer to the

two sides, and the horizontal stress is concentrated to the roof and floor, but forms a complex three-dimensional high stress envelope area and unloading relaxation area. The magnitude and direction of the maximum principal stress and the minimum principal stress are strongly deflected around the roadway, and multiple stress concentration areas are often formed at the arch foot, wall foot and floor corner. This complex stress path makes the yield criterion of surrounding rock more easily satisfied. The range of plastic zone is no longer symmetrical 'D' shape or 'O' shape, but the depth increases significantly (up to 0.5-1 times or even deeper than the roadway span), and the shape is extremely irregular. There may be a phenomenon of nesting or connecting multiple plastic zones, which provides a broad space for large deformation and failure of surrounding rock.

In the super-large section roadway, the rock mass is not a uniform continuous medium. There are a large number of joints, fissures, bedding, faults and other structural planes in the rock mass, which play a controlling role in the stability of the surrounding rock. After excavation and unloading, the stress redistribution makes the structural plane open and slip, and the original embedded structure is destroyed. Large-scale key blocks cut by structural planes may rotate, slip or collapse due to the loss of lateral constraints. The instability of a key block will change the stress state of the surrounding rock mass, often triggering a chain reaction, forming a 'domino' effect, resulting in a sharp adjustment of stress and rapid transfer to the supporting structure, so that the load increases sharply, which is very easy to cause the overall instability. Therefore, the failure mode of super-large cross-section roadway is often a composite failure of rigid body motion controlled by structural plane and progressive shear or tensile fracture of complete rock bridge.

2.2. Surrounding rock deformation and failure mode of super large section roadway

2.2.1. Roof bending tensile failure and separation layer

The super-large span makes the roof rock layer like a huge, thick 'rock beam' or 'plate'. Under the combined action of the self-weight of the overlying strata and the far-field tectonic stress, a huge tensile stress is generated on the lower surface of the middle of the 'rock beam', while a compressive stress is generated on the upper part of the vault. When the maximum tensile stress exceeds the tensile strength of the rock mass, longitudinal tensile cracks will first appear in the middle of the roof. At the same time, at the junction of rock strata with different lithology, the phenomenon of separation will occur due to the difference of deformation modulus. The cracks expand from top to bottom, and the separation layer develops from bottom to top. The two are connected to each other, and finally the roof strata are cut into independent blocks or thin layers, losing the overall bearing capacity, resulting in a large-scale and sudden roof caving accident.

2.2.2. Strong bottom drum

The floor is the weak link of the surrounding rock support of the super large section roadway, and often does not get the same support attention as the roof and the two sides. Its damage is mainly manifested as severe floor heave. There are two main mechanisms: first, the excavation unloading makes the floor rock unloading rebound; second, under the action of high-level tectonic stress, the deep rock mass plastically squeezes into the low-resistance roadway space. In soft rock, broken rock or water softening rock, the phenomenon of floor heave is particularly severe. The floor heave not only directly encroaches on the effective clearance of the roadway, affects the operation of the equipment and the safety of the personnel, but also pushes the foundation of the two sides, resulting in the instability of the wall foot, which in turn induces the further deformation and failure of the side wall and the roof, forming a vicious circle.

2.2.3. Collaborative failure of supporting structure

Due to the large deformation, long duration and uneven distribution of surrounding rock, if the design of supporting structure is improper or the construction quality is poor, it is easy to cause synergistic failure. For example, high-strength bolts may be pulled off or thread slide due to excessive deformation of surrounding rock ; prestressed anchor cable may have prestress loss or even fracture due to creep of rock mass in anchorage section. The shotcrete layer may be peeled off in a large area due to bending deformation, and lose its sealing and combination effect ; the steel arch may be distorted, bent or even destabilized due to local stress overrun. This failure is often not the problem of a single component, but the result of the uncoupling of the entire support system and the surrounding rock and the inability to coordinate the deformation.

2.3. Influencing factors of surrounding rock deformation and failure

2.3.1. Section size and shape effect

The section size is the decisive factor. Both theoretical analysis and practice show that the roadway span (B) is the most important parameter affecting the stability of surrounding rock and the range of plastic zone (R). There is usually a relationship between $R \propto B^n$ ($n > 1$), that is, the range of plastic zone increases nonlinearly and rapidly with the increase of span. The section shape directly affects the stress concentration factor and distribution. The circular or elliptical section has the most uniform stress and the lowest stress concentration, but the construction is difficult and the space utilization rate is low. The semi-circular arch (or three-center arch) section of the straight wall is the most widely used, but the stress concentration is easy to occur at the arch foot and the wall foot ; the stress distribution of rectangular section is the most unfavorable, but the construction is simple.

2.3.2. Rock mass structure and engineering geological conditions

The strength parameters (cohesion, internal friction angle) and deformation parameters (elastic modulus, Poisson 's ratio) of rock mass are the internal determinants. But more important is the rock mass structure, that is, the occurrence, spacing, continuity, roughness, filling and so on. When a set of parallel weak structural planes is adversely combined with the roadway strike, it is easy to cause roof collapse or side wall slip. The existence of groundwater will soften the rock mass, reduce the shear strength of the structural plane, produce seepage pressure, and greatly deteriorate the surrounding rock conditions. The size and direction of the in-situ stress field are very important, especially the high-level tectonic stress will significantly aggravate the roof and floor damage and floor heave.

2.3.3. Construction factors and supporting characteristics

The construction method (full-face excavation, step-by-step excavation) and excavation footage directly affect the degree of disturbance to the surrounding rock. The timing of support (' timely support ') is the key. Too early support may bear excessive load, and too late support may miss the best time to control deformation. The stiffness, strength, installation quality and coupling degree with surrounding rock (close condition) of the supporting structure directly determine whether it can effectively play a supporting role.

3. Surrounding Rock Deformation Control Technology of Super Large Section Roadway

3.1. Design and optimization of step-by-step coupling support structure

3.1.1. Traditional support method and its limitation

The design concept of traditional bolt-shotcrete net support or single steel support is based on a relatively small deformation assumption, and it is difficult to independently bear the huge and

uneven surrounding rock pressure of super-large section roadway. The problem of "strong support and weak synergy" often occurs: the strength of the support body itself may be high, but the stiffness does not match, the deformation cannot be effectively controlled, or the local failure cannot occur in advance with the coordinated deformation of the surrounding rock, which leads to the overall failure.

3.1.2. Step-by-step coupling support concept and new structure application

According to the deformation characteristics of super large section roadway, the core concept of 'step-by-step coupling support' is put forward. Its connotation is to apply different stiffness and strength support in stages in time, and to form a whole and coordinated bearing between each support unit and surrounding rock in space.

The initial support (active, flexible pressure support): followed by the excavation face in a timely manner. The core is a high pre-stressed, full-length anchored bolt-anchor system. The high prestressed anchor bolt (cable) can actively compress the rock mass, improve the shear resistance of the structural plane, and significantly improve the strength of the bearing ring of the shallow surrounding rock. Combined with steel mesh and shotcrete, a flexible supporting layer is formed, which can not only provide a certain supporting force, but also allow the surrounding rock to produce controllable deformation ('yield') within a certain range. The retractable anchor (cable), pressure pipe and other components are very effective at this stage. Secondary support (permanent and rigid bearing support): After the deformation of surrounding rock is confirmed by monitoring to enter the stable stage of convergence (such as convergence rate less than $0.2\text{mm}/\text{d}$), it is applied. Cast-in-place reinforced concrete lining is usually used. Its function is to provide the final safety reserve, bear the residual surrounding rock pressure, ensure the long-term stability and durability of the roadway, and meet the functional requirements of waterproof and fire prevention.

The primary support and the secondary support are sequentially and dynamically coupled in time and space to form a complete support system.

3.2. Improvement of construction method and process

3.2.1. Step excavation and core soil retention

Resolutely abandon the traditional practice of full-section excavation. According to the geological conditions and section size, the step-by-step excavation methods such as the up and down step method, the double side wall guide pit method (middle partition method CD, cross middle partition method CRD) are scientifically selected. The large section is divided into parts, divided into blocks and excavated step by step, which effectively controls the size of the free face and the exposure time of each excavation, and realizes the fine management of surrounding rock disturbance and stress release. For extremely weak surrounding rock, the method of reserving core soil can be used to provide temporary support by using core soil to stabilize the working face.

3.2.2. Refined controlled blasting technology

Smooth blasting or pre-splitting blasting technology must be used in drilling and blasting excavation. Through the precise design of blasting parameters (blast hole spacing, charge amount, charge structure, detonation sequence, etc.), the blasting vibration is strictly controlled, and the smooth excavation contour is formed to minimize the damage to the retained surrounding rock and the overbreak and underbreak, so as to reduce the stress concentration from the source and create good conditions for the subsequent support.

3.2.3. Advanced pre-support and timely closure

In the fault fracture zone, extremely weak surrounding rock section or shallow buried section, advance pre-support must be carried out before excavation. The commonly used methods include: advanced anchor, advanced small pipe grouting, pipe shed (steel flower pipe or glass

steel anchor pipe), etc. The purpose is to form a pre-reinforced ' umbrella ' or ' arch ' in front of the excavation face to protect the safety of the excavation operation and control the advance deformation. After excavation, it is necessary to immediately spray concrete (3-5cm thick) to quickly seal the fresh surrounding rock, prevent its weathering, deliquescence and strength attenuation, and provide a safe environment for subsequent installation of anchors, hanging nets and other operations.

3.3. Surrounding rock reinforcement and modification technology

3.3.1. System grouting reinforcement

The slurry is injected into the cracks and pores of the surrounding rock by grouting to improve the strength of the surrounding rock of the roadway. Grouting materials can be selected according to the properties of surrounding rock, such as cement slurry, chemical slurry and so on. For the broken rock mass, the cement slurry can effectively cement the broken rock mass and enhance the bearing capacity of the rock mass ; for the rock mass with less permeability, the chemical slurry can penetrate and solidify better. Reasonable design of grouting parameters, such as grouting pressure, grouting volume, grouting time, etc., to ensure the grouting effect and improve the mechanical properties of surrounding rock.

3.3.2. Deep reinforcement of prestressed anchor cable

Long and large tonnage prestressed anchor cable is the key component to control the deformation of super large section roadway. Its length is usually deep into the stable rock strata outside the potential plastic zone (more than 8m). By applying high prestress (150kN-300kN or even higher), the deformation of surrounding rock is actively constrained, and the load of shallow unstable rock mass is transferred to the deep stable rock strata. Fully mobilize the bearing potential of deep surrounding rock, effectively control roof subsidence and constrain the further development of plastic zone.

4. Actual-service Test

4.1. Engineering overview and geological conditions

The return airway of 8000 working face is located in the north of 80 mining area. The total length of the roadway is 1958.3 m, and the elevation of the working face is + 341.4 ~ + 211.7 m. The east is the preparation roadway of 80 mining area, the west is the drainage roadway of 80 mining area, the south is the 80-0002 bottom pumping roadway, and the north is the solid coal body. The return airway of the 8000 working face opens from the west side of the auxiliary transportation roadway in the 80 mining area. The opening position is located 10.1 m in front of the 0840 measuring point, and it has an angle of 110 ° with the auxiliary transportation roadway in the 80 mining area. The design length is 1910 m, and the straight wall is semi-circular arched section : 7 m wide, 5.9 m high, 1.6 m high, net cross-sectional area of 49.2 m², which belongs to the typical super-large section roadway of coal mine. The original design adopts the support scheme of ' anchor net spray + ordinary anchor cable ' : anchor bolt $\Phi 22 \times 2400\text{mm}$, row spacing $800 \times 800\text{mm}$; anchor cable $\Phi 22 \times 6300\text{mm}$, spacing $1200 \times 800\text{mm}$; the thickness of shotcrete is 150mm. During the excavation process, the deformation of the roadway is severe. Within one month after the excavation, the maximum subsidence of the roof is 220 mm, the maximum convergence of the two sides is more than 350 mm, and the amount of floor heave is about 150 mm. There are a large number of mesh cracks and local spalling in the shotcrete layer, some bolt trays fall into the rock mass, the prestress loss of the anchor cable is serious, the stability of the roadway is poor, and the transportation safety is seriously threatened.

4.2. Implementation of comprehensive control technology scheme

Excavation process optimization : the upper and lower step method is used for excavation, the upper step height is 3.7 m, the lower step height is 3.8 m, and the cyclic footage is strictly controlled at 1.0 m. Smooth blasting is adopted, the spacing of surrounding holes is 450 mm, and the density coefficient is 0.8, so as to reduce over-excavation and disturbance to surrounding rock.

Advanced pre-support : In the section with poor lithology, the advance bolt ($\Phi 22 \times 4000\text{mm}$, interpolation angle $10^\circ - 15^\circ$) is applied within 120° of the arch, and the spacing is 300mm.

The initial support is strengthened :

(1) Timely sealing : C20 concrete 50mm thick closed surrounding rock was sprayed immediately after excavation.

High-strength bolt : install high-strength prestressed rebar bolt ($\Phi 22 \times 2400\text{mm}$, yield strength 500MPa), row spacing $800 \times 800\text{mm}$. Immediately after installation, a preload of no less than 60 kN is applied.

(2) Long prestressed anchor cable : using low relaxation steel strand anchor cable ($\Phi 22 \times 6300\text{mm}$), in-depth stability of rock. The row spacing is adjusted to $1200 \times 800\text{mm}$.

(3) Reinforcement mesh and re-spraying : laying $\Phi 8\text{mm}$ reinforcement mesh (mesh $100 \times 100\text{mm}$), and then re-spraying concrete to a total thickness of 150mm.

(4) Floor control : after the bottom, timely pouring 200mm thick C30 reinforced concrete inverted arch, closed floor, inhibit the floor heave.

Secondary lining (reservation) : secondary lining conditions are reserved. After the monitoring deformation is stable, it is decided whether to pour 300 mm thick reinforced concrete permanent lining or not according to the situation. The specific anchor cable layout is shown in Figure 1.

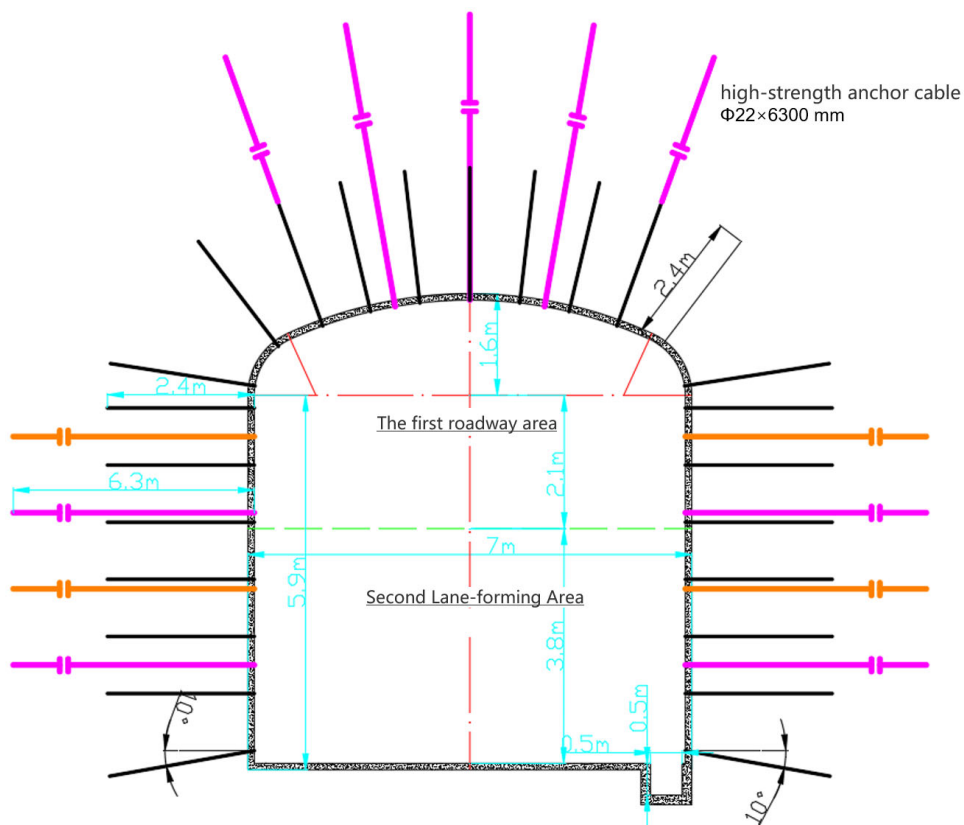


Figure 1. Anchor cable layout diagram

4.3. Implementation effect monitoring

By implementing the comprehensive control technology, the roadway deformation is effectively controlled. In the first month after excavation, the roof subsidence rate decreased rapidly from the original daily average $> 5\text{mm}$ to less than 1.5mm/d . The convergence rate of the two sides is reduced to less than 2.0mm/d . After 3 months, the deformation is basically stable, the cumulative displacement of the roof and floor is finally stabilized within 140mm , and the cumulative convergence of the two sides is stabilized within 110mm . The prestress loss rate of anchor cable is less than 10% , and the supporting structure is intact without obvious cracking or damage. The results show that the comprehensive technical system of 'sub-excavation + high-prestressed anchor net cable-shotcreting active support' has been successfully applied. Step-by-step excavation effectively controls the stress release rate; the high pre-stressed anchor cable system actively reinforces the surrounding rock and forms an effective bearing ring. The overall support structure and the surrounding rock deformation have achieved good coupling, and the synergistic bearing efficiency is remarkable, which completely reverses the unstable situation under the original support scheme and ensures the long-term safety and stability of the roadway. The surface displacement of the roadway is shown in Figure 2.

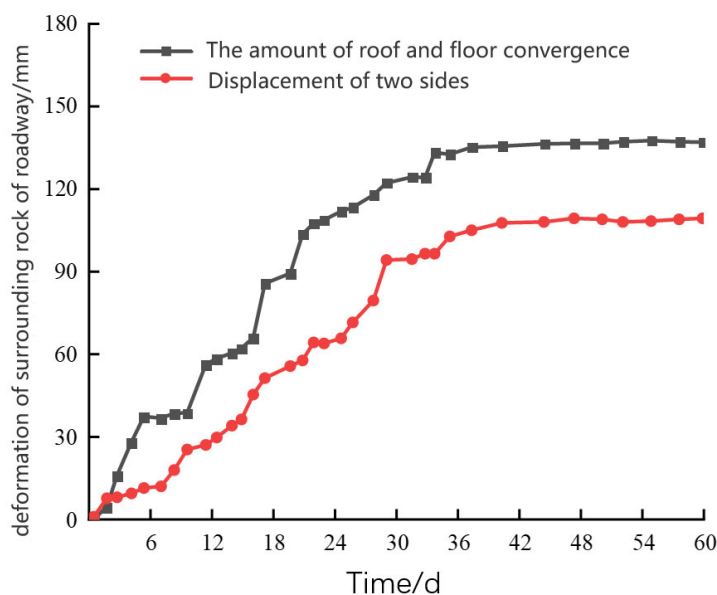


Figure 2. Roadway surface displacement monitoring

5. Conclusion

(1) The deformation and failure mechanism of surrounding rock in super-large cross-section roadway is complex and unique. Its core lies in the strong ' size effect ', which is manifested as complex stress redistribution after excavation, progressive space-time development of plastic zone expansion and macroscopic instability controlled by structural plane. The main failure modes include bending tensile-separation of roof, buckling-shear of high side wall, strong floor heave and synergistic failure of supporting structure, which are significantly different from conventional roadways.

(2) The stability of surrounding rock is controlled by multiple factors such as section size and shape, rock mass structure and strength, in-situ stress environment, groundwater and construction factors. The deterioration of any single factor may significantly aggravate the risk of deformation and failure.

(3) A comprehensive control technology system with the core of " step-by-step excavation pressure relief, active coupling support, and overall reinforcement of surrounding rock " is proposed. The industrial test is carried out in the return air roadway of 8000 working face. The results show that the scheme can significantly control the deformation of surrounding rock within the allowable range, ensure the long-term effectiveness of the support structure, and ensure the safety and stability of the roadway.

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