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Failure Analysis of a Soft Broken Roadway and a New Bolt-Grouting Support Technology

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Abstract: In this paper, taking a typical roadway in broken and soft rock strata in No.10 Mine of Pingdingshan coal field as an example, the deformation and failure mechanism of rock mass was deeply analyzed based on field testing. Then the technology of high-strength prestressed bolt-grouting support, such as the new combined high-strength grouting bolt, high-strength hollow grouting anchor cable, were developed. Based on this, a repair support scheme using the new technology was designed for on-site roadway, and was successfully implemented in the field. The monitoring results after the repair of field roadway show that the maximum of roadway surface convergence deformation is 56mm. The maximum force of the grouting bolt is 122kN, the grouting anchor cable is 256kN. The new technology can fill the cracks of rock mass and the borehole interstice at the free part by using grouting materials. It can effectively enhance the self-bearing performance of soft broken rock mass on the premise of ensuring the diffusion of prestressed active supporting effect in rock mass, and then suppress the deformation and failure of roadway. The research works can provide references for the stable control and support design for roadways in soft and broken rock strata.

Keywords: soft and broken rock strata; roadway; high-strength support; prestressed bolt-grouting; stable control

1. Introduction

In recent years, due to the continuous development of China 's economy and society, the consumption of coal resources is increasing, and the intensity of coal mining is increasing year by year. Mine roadways will invariably encounter a variety of complex

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geological conditions while mining coal resources, including high ground stress, high permeability water pressure, weak strata, fault fracture zone, severe mining disturbance and so on. And easy to cause large deformation, fall of ground, rock burst and other disasters, constantly threatening the safety and efficient production of mine. As a preferred form of mine roadway support at present, prestressed bolt (anchor cable) can effectively play the active support effect, mobilize the self-bearing performance of rock mass, and limit the deformation and failure of rock mass. In weak and broken strata, the rock mass tends to be loose and broken due to its low strength. However, the traditional anchorage support is faced with a series of problems, such as no stable anchorage rock, poor anchoring ability and difficult to give full play to the support potential[1].

Many academics have conducted a great deal of theoretical and technological application study in response to the issue of anchoring and sustaining rock mass of highways in weak and fractured strata. At present, the traditional anchorage support theories of weak strata include rock mass strengthening theory, neutral point theory and so on [2-4]. The above theories provide a good theoretical basis for roadway support design in weak strata. Kang et al. [5] developed the theory of high-strength prestressed anchorage support on the basis. The study on the mechanism of bolt support in deep roadway has certain theoretical support for the study of anchorage support. Indraratna and Kaiser [6], Li and Stillborg [7], Cai et al. [8], Osgoui and Oreste [9], Bobet and Einstein [10] et al. obtained the distribution characteristics of bolt stress under the interaction between bolt rob and tunnel rock mass based on the elastic-plastic theory. Wang et al. [11] analyzed the variation trend of grouting diffusion performance under various grouting bolt lengths through theoretical derivation and practical investigation, and revealed the influence law of different grouting parameters on rock mass and support system.

In terms of control technology research, He et al. [12], Li [13] Aiming at the problem of large deformation and failure of roadway in soft rock strata, a large deformation bolt (anchor cable) support technology is proposed, carried out systematic indoor static test and dynamic impact test, and successfully applied and popularized it. Kang et al.[14] developed a comprehensive set of core technologies for prestressed anchoring of high-strength rob, construction, pallets, and steel strips, which effectively solved the problem of rock mass control in roadway. Li et al. [15] put forward the failure mechanism of bolt support aiming at the serious problem of bolt deformation and failure, analyzed the influence law of different rock mass mechanical parameters on interface bond strength, and developed a new technology.

Currently, it has been established via extensive testing that anchoring technology can successfully increase the strength and integrity of the adjacent rock by grouting alteration, which is an effective support method for weak broken rock mass. For instance, Wang et al.[16] proposed a U-shaped steel bolt-grouting combined support technology based on engineering examples and model analysis, aiming at the problem of soft rock roadway support, and verified the feasibility of the scheme. Yang et al.[17] presented a flexible bolt-grouting technology of working face support aiming at the issue of collapse control of longwall working face in thick coal mining area, which has been applied in Chenmanzhuang Mine and shown that this technology can improve the stability of working face and reduce the investment cost. Yang et al.[18] proposed a prestressed bolt-grouting reinforcement method for underground broken rock controlled by anchor mesh in Daxing mine rail transportation roadway, aiming at the problem that the anchor mesh could not be controlled. Wang et al.[19] designed a series of bolt-grouting support contrast tests to solve the issue of roadway rock mass control in three soft coal seam in

Longkou mining area, and carried out field application and implementation to verify the bolt-grouting control effect of soft rock mass in the field.

It should be noted that the existing conventional bolt-grouting components generally have low strength and are difficult to apply prestress and so on, which are often used as secondary reinforcement or repair reinforcement in the construction process of mine roadway, and are difficult to replace the primary bolt (anchor cable) support. For example, the breaking force of the conventional MLX50-27/32Z*2000 hollow grouting screw bolt rob is only about 50kN. And there are many factors that affect the failure of roadway rock mass in weak and broken strata, so the safety and stability control of such roadway still needs us to continue to study. This study, a typical roadway in soft and broken rock strata in No.10 Mine of Pingdingshan coal field is taken as an example. The deformation and failure mechanism of rock mass is deeply analyzed based on the field roadway failure testing. On account of the technology of high-strength prestressed, key technologies such as new high-strength combined grouting bolt and hollow grouting anchor cable are developed. The field application and implementation are carried out, and the difficult problem of stability control of the field roadway rock mass is effectively solved. It can provide some reference for the support design and construction of such strata roadway.

2. Deformation and Failure Characteristics of a Typical Roadway in Weak Strata

2.1 Project Profile

The Pingdingshan coalfield is located in central Henan Province, China, as shown in Figure 1. It is one of the important high quality bituminous coal bases in China. There are 18 mines and coal mines in the coal field. The coal bearing strata in Pingdingshan coal field are Carboniferous and Permian, which contain 9 groups of coal, and 13 layers of coal seam can be mined. Among them, No.10 coal mine is located in the east of Pingdingshan City, Henan Province. The mine was started in August 1958 and officially put into operation in February 1964. The well field is 4 kilometers long from east to west and 5.13 kilometers wide from north to south, with an area of 20.52 square kilometers. The mine has a designed production capacity of 2.9 million tons, a holding reserve of 210 million tons and a recoverable reserve of 150 million tons.

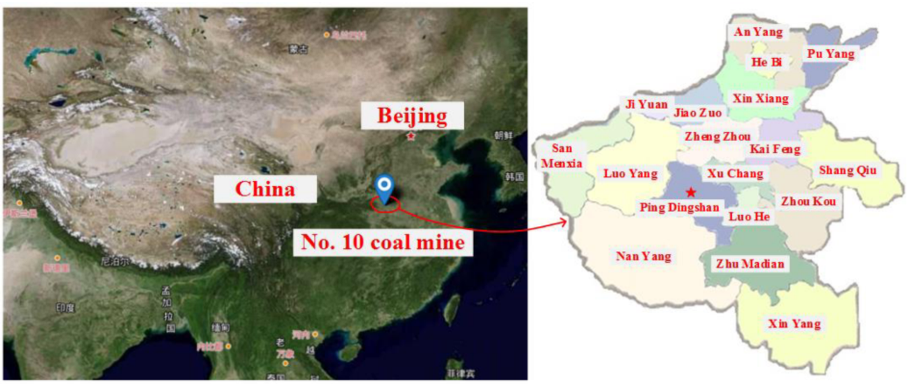


Figure 1. Location of No.10 coal mine in Pingdingshan city, Henan, China

The downhill roadway of group E in the central district of No.10 coal mine was built in the 1970s, with a history of 50 years ago. It consists of four tunnels, namely, track downhill roadway of group E, transport downhill roadway of group E, gas special roadway of group E, and concentrated transport roadway of group E. The layout plan is shown in Fig. 2. Among them, the track downhill roadway in the central area is 36m away from the transport downhill, 53m away from the gas special lane, and 80m away from the concentrated transport lane of group E. The upper part of the track downhill has been basically mined.

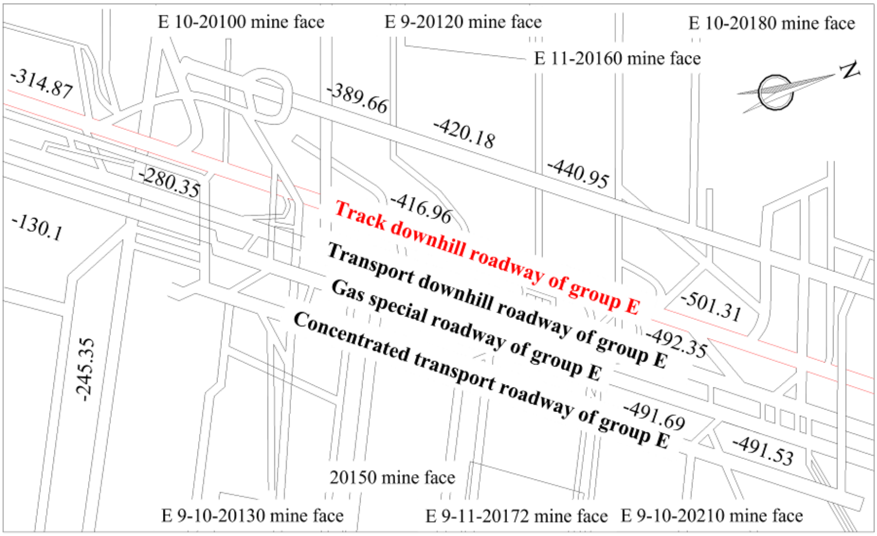


Figure 2. Layout plan of downhill roadways of group E in central area

The roof of coal seam E 8 is arranged along the lower hill of track group E in the central area of No.10 coal mine. The original driving section is 14.4m2 and the length is 970 meters. The original design adopts bolt-mesh support, which is partially supported by U36 steel arch support after many repairs. The original roof of the roadway is sandy mudstone, the two sides are mudstone, coal seam and sandy mudstone from bottom to top, and then the upper side is thick fine-grained sandstone. The floor of the roadway is mudstone, and some sections pass through the E 8 coal seam. The track is seriously damaged by dynamic pressure when going downhill. After many repairs, the longest stability period of the roadway after repair is less than a year. The coal seam has been exposed in the 600-meter section of track to the drop-off yard after many times of bottom pulling construction. At present, the track downhill roadway is seriously damaged, which has endangered the safety of pedestrians and transportation. The roadway section changes from semi-circular arch to sharp roof shape, which shows that the roof is seriously sunk and the two sides move into the roadway as a whole. Moreover, the roadway deformation has not stopped, and the roadway is facing the danger of complete destruction. Fig. 3 lists the sections before and after the expansion of typical parts of the downhill roadway of group E track in the central area. Compare initial design cross-section, the transformation convergence of the rock mass of the site roadway exceeds 1.7m.

Figure 3. Cross-sections before and after roadway repair

2.2 Analysis of Deformation and Failure Characteristics of Roadway Rock Mass

In order to further reveal the failure characteristics of the roadway on site, the author drilled detection holes along the roof, arch shoulder and two sides of the roadway in the early stage, and used the drilling peephole to detect the loose failure range of rock mass. The design depth of the exploration hole was 10m. Fig. 4 lists the rock mass loosening failure results of typical sections of field roadway. As can be seen from Fig. 4, the loose failure range of the rock mass of the roadway on site is large, and the rock mass within 10m range of the exploration borehole has produced different degrees of cracking failure. Specifically, the rock mass can be divided into serious failure zone, medium failure zone and slight failure zone from inside to outside along the roadway surface, and the failure zone is distributed in a ring. Among them, the rock mass in the severely damaged area is very loose and broken, and the range is large. The serious failure zone of the roadway roof rock mass has exceeded 2.8m, and the serious failure zone of the side has reached 3.2m, all of which have exceeded the original designed bolt length.

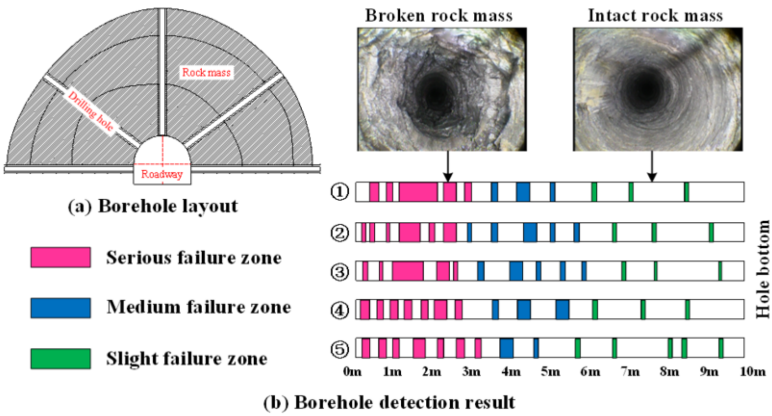


Figure 4. Detection results of failure range of rock mass in field roadway

Combined with the engineering geological conditions and rock mass deformation and failure test results of the track downhill roadway of group E in the central area of the No.10 coal mine, the causes and mechanisms of large deformation and failure of the on-site roadway mainly include the following aspects:

(1) The formation lithology is poor and the self-bearing capacity of rock mass is low

Because the track of group E in the central area descends into the mudstone, coal seam and sandy mudstone strata, and part of the sections pass through the coal seam of E 8, the rock mass environment of the roadway is soft and weak with poor lithology. Moreover, after nearly 50 years of deformation and failure of the roadway in the site, the range of loose failure is enormous, and it is in a very loose and broken state, especially the roof and shoulder are seriously broken, which further weakens the bearing capacity of rock mass itself. Therefore, the basic causes of large deformation and failure of roadway rock mass are the poor lithology of roadway strata and the low bearing capacity of rock mass.

(2) The stress concentration effect and the disturbance and destruction effect of cyclic mining are significant

The roof of coal seam E 8 is arranged along the lower hill of track group E in central area, and the normal distance from coal seam E 9 is only 3-4 meters.

The track downhill roadway is located in the concentration area of mining in working face and roof collapse stress in goaf. Due to the cyclic and repeated action of mining face and goaf roof collapse pressure, the stress in local sections is concentrated, and the dynamic pressure action in different stages and the dynamic load disturbance effect of complex stress environment are more significant, which makes the deformation and failure of the roadway roof in the field quite serious. Therefore, the stress concentration effect and the circulation mining disturbance effect are also an important reason for the serious damage of field roadway.

(3) It is difficult to form an effective active cooperative bearing structure because of the unreasonable support method

Due to the repeated repair and mining disturbance of the roadway, the rock mass is in a very soft and broken state, and the range of loose failure is too large. It is difficult to provide a stable anchorage foundation for the original supporting members and cannot effectively mobilize the self-bearing capacity of rock mass. At the same time, the U-shaped steel arch partially adopted after site restoration belongs to a passive support form, with limited overall strength and stiffness. It is also difficult to provide sufficient support strength for weak and broken rock mass on site, and it is more difficult to actively mobilize the self-bearing capacity of rock mass.

Therefore, the on-site support method is not reasonable, and it is difficult to form an effective active cooperative bearing structure between support and rock mass to jointly resist the deformation and failure of rock mass. It is also an important reason that the rock mass is still broken seriously and cannot be stabilized after roadway repair.

3. Field Application and Implementation of High-Strength Prestressed Bolt-Grouting Technology

3.1 New High-Strength Prestressed Bolt-Grouting Technology

Aiming at the problem of controlling the weak and broken rock mass on site of the track downhill roadway of group E in the central area of Pingmei No.10 coal mine, in order to ensure the safety and stable control of the roadway, the author developed new key technologies of bolt-grouting, such as combined high-strength grouting bolt, high-strength hollow grouting anchor cable ,as shown in Fig. 5 and Fig. 6.

(1) Combined high-strength grouting bolt

The combined high-strength grouting bolt is composed of high-strength hollow grouting section and high-strength bolt section, which are combined by high-strength connecting sleeve. The outer diameter of the high-strength hollow grouting section is about 30mm, the wall thickness is 6-8mm, and the breaking force reaches 250~300kN. The high-strength bolt section adopts left-rotating rebar without longitudinal bars, with a diameter of 22mm and a breaking force of more than 300kN.

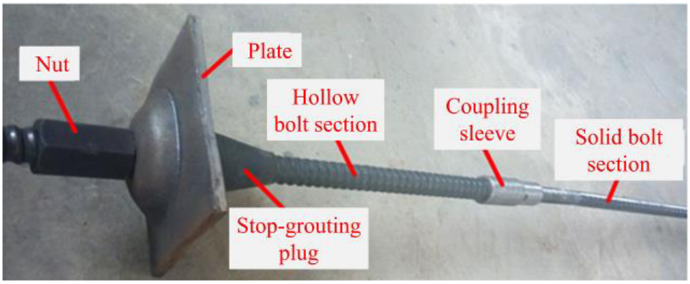


Figure 5. Combined high-strength grouting bolt

(2) High-strength hollow grouting anchor cable

The high-strength hollow grouting anchor cable rob is a hollow structure made of multi-strand high-strength prestressed steel wire and grouting core tube. The outer diameter is 22mm, the inner diameter of grouting tube is 8mm, the breaking strength is 1860MPa, and the breaking force is more than 400kN.

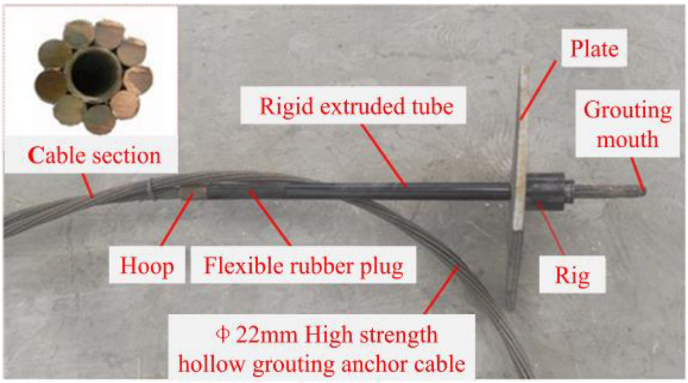


Figure 6. High-strength hollow grouting anchor cable

3.2 Support Scheme Design

On this bases, a prestressed bolt-grouting scheme with combined high-strength grouting bolt and high-strength hollow grouting anchor cable as the core is designed. It is used to replace the existing anchor mesh support and U-shaped steel arch support and improve the control effect of site rock mass.

Specifically, the section shape of the field roadway after expansion and repair is straight wall semicircular arch, with a width of 5100mm and a height of 3800mm.

After the expansion and repair to the qualified section, the left rotation high-strength resin bolt and the combined high strength grouting bolt are used for the initial support.

The initial grouting measures are taken to seal the rock mass fissure and prevent the rock mass from weathering and fracturing. On this basis, the high-strength hollow grouting anchor cable is used to strengthen the support, and the secondary grouting and grouting reinforcement are implemented. Finally, the combined high-strength grouting bolt and high-strength hollow grouting anchor cable are used to strengthen the floor grouting.

Fig. 7 lists the section design drawings of high-strength prestressed bolt-grouting support at different construction stages. Specific support parameters are as follows:

(1) Roof and side support parameters

①High-strength resin bolt and combined high-strength grouting bolt: both of them are arranged alternately, and the row spacing between them is 700×1400mm. High-strength resin bolt diameter is 22mm, and the length is 2400mm. The combined high-strength grouting bolt has an outer diameter of 22mm and a length of 2500mm. The high-strength resin bolt adopts two rolls of MSZ2850 resin coil end-anchored, and the combined high-strength grouting bolt adopts a roll of MSZ2850 resin coil end-anchored, the prestressed is not less than 50kN. The 150×150×8mm square plate is used for installation.

②Spray layer: When high-strength resin bolt and combined high-strength grouting bolt are installed on the roadway surface, steel mesh is used to protect the table. The diameter of steel bar is 6mm, the mesh size is 50×50mm, and the lapping length between each other is not less than 100mm. The thickness of the first shotcrete is 50mm, the thickness of the second shotcrete is 100mm, and the strength grade of the concrete is not less than C20.

③High-strength hollow grouting anchor cables: 7 anchor cables are arranged in each row, with a spacing of 1400mm×1400mm, a diameter of 22mm, and a length of 7300mm. Using two rolls MSZ2850 resin coil end-anchored, the prestress is not less than 120KN. The plates are 300×300×14mm square plates.

(2) Floor support parameters

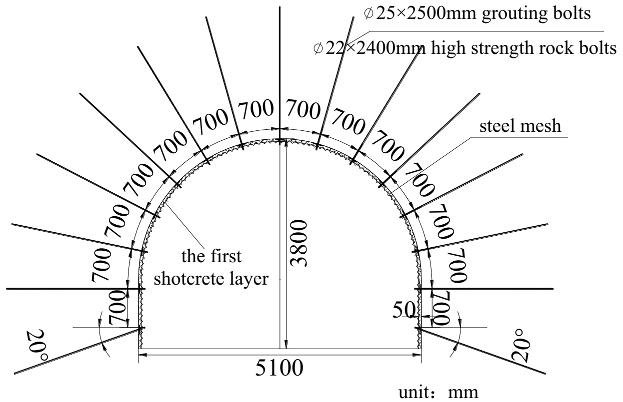
①Combined high-strength grouting bolts: 5 bolts are evenly arranged along the roadway floor, with a spacing of 1000×1000mm between rows, and are connected by 16# reinforcement ladder, with a diameter of 22mm and a length of 2500mm. Cement grouting end-anchored is used, and the design prestress is not less than 50KN. The plates are 150×150×8mm square plates.

②Floor: the thickness of the first and second laying concrete floor is 100mm, the concrete label is C20;

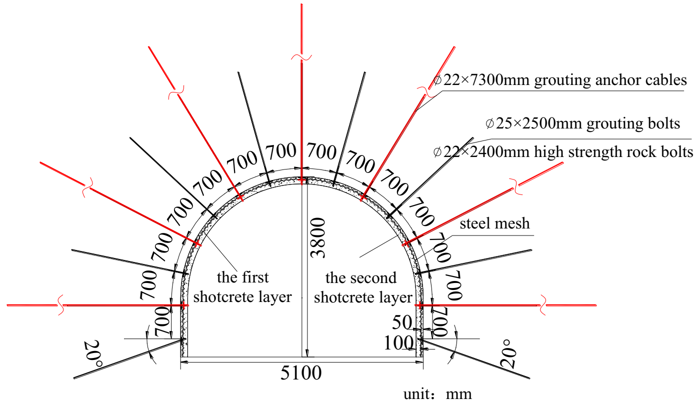
③High-strength hollow grouting anchor cables: 3 are uniformly arranged along the roadway floor, with a spacing of 1500mm×2000mm, a diameter of 29mm, and a length of 7300mm. Cement grouting end-anchored is used, and the design prestress is not less than 120KN. The plates are 300×300×14mm square plates.

(3) Grouting parameters

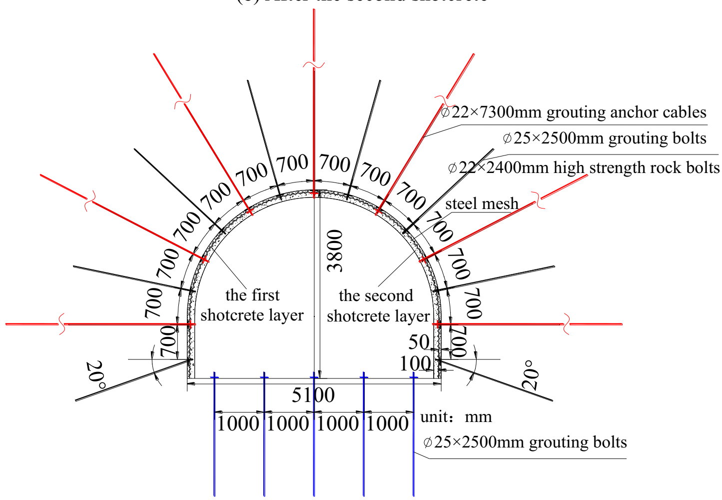
In the field roadway grouting construction, MZM-70 high-strength inorganic grouting material is used as grouting material, and cement-water ratio is less than 3:1. Among them, the grouting pressure of the combined high-strength grouting anchor bolt is 3~5Mpa, and the grouting pressure of the high-strength hollow grouting anchor cable is not less than 7MPa.



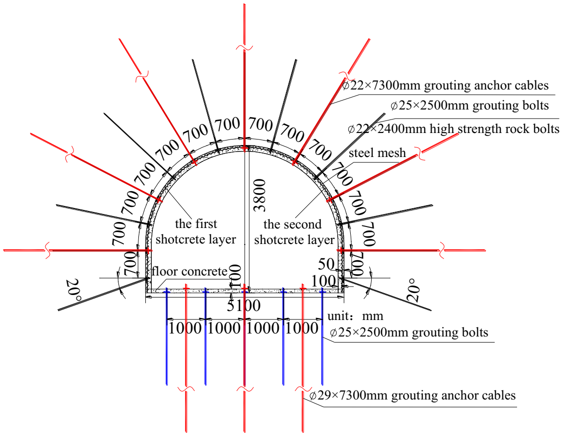
(a) After the first shotcrete



(b) After the second shotcrete



(c) After installation of the floor grouting bolts



(d) After installation of the floor grouting anchor cables

Figure 7. Cross-sectional design drawing of high-strength prestressed bolt-grouting support under different stages

3.3 Monitoring and Analysis of Site Rock Mass Control Effect

In order to further verify the rock mass control effect of the proposed support scheme and the effectiveness of the new high strength prestressed bolting technology. After the field roadway was expanded and repaired with high-strength prestressed bolt-grouting technology, the author carried out the testing and monitoring work of rock mass drilling and coring, roadway surface convergence, rock mass internal displacement, and support components stress in typical sections of the field roadway. The specific results are as follows:

(1) Rock mass drilling and coring test

The typical location of field roadway was selected, and the rock mass was drilled and cored after field grouting. The laboratory uniaxial compression mechanical test was carried out on the processing and production of the extracted core, as shown in Fig. 8. As can be seen from Fig. 8, after the high-strength prestressed bolt-grouting support technology is adopted on site, high-strength inorganic grouting slurry can effectively fill the weak and broken rock mass cracks on site. After grouting, the uniaxial compressive strength of typical rock mass specimens exceeds 30MPa, and the integrity and strength of rock mass are effectively improved.

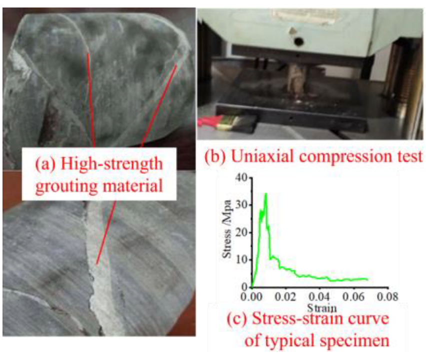


Figure 8. Core-drilling of rock mass after grouting and laboratory test

(2) Roadway surface convergence monitoring

Fig. 9 lists the monitoring results of rock mass surface convergence of typical sections after field roadway expansion and repair. As can be seen from Fig. 9, after adopting the high-strength prestressed bolt-grouting and expansion support scheme in the field roadway, the convergence deformation rate of rock mass is relatively large within 0-19 days, and gradually tends to be stable after 20 days. At 70 days, the maximum subsidence of roof is 56mm, the maximum convergence deformation of side is 33mm, and the maximum deformation of floor is 39mm. The deformation and failure of field roadway rock mass have been effectively controlled.

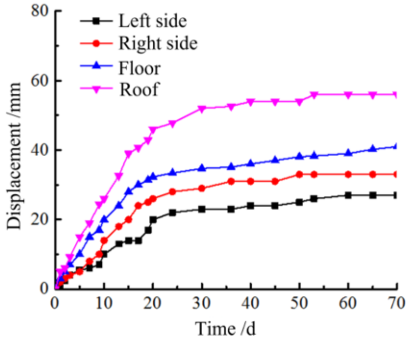
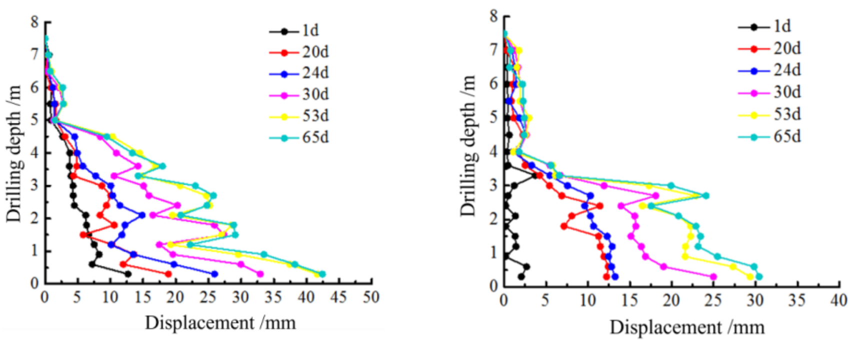


Figure 9. Typical monitoring curves of roadway surface convergence displacement

(3) Internal displacement monitoring of roadway rock mass

In order to further monitor the control effect of roadway rock mass on site, boreholes were drilled along the roof, shoulder socket and two sides of the roadway, and multi-point displacement records were installed to monitor the internal displacement of roadway rock mass. The borehole depth is 8m. Fig. 10 lists the internal displacement monitoring results of typical roadway section roof and side. As can be seen from Fig. 10, the deformation and failure of the rock mass of the roof of the field roadway are mainly concentrated in the range of 5m, the deformation and failure of the rock mass of the side are mainly concentrated in the range of 3.5m, and the maximum internal displacement is concentrated in the range of 30-45mm. Moreover, the internal displacement curve at 66d is basically unchanged compared with that at 53d. It also shows that the deformation and failure of rock mass have been effectively controlled.



(a) Roof (b) Roadside department

Figure 10. Typical monitoring curves of roadway internal displacement

(4) Support member stress monitoring

Figs. 11-12 list the stress monitoring results of high-strength grouting bolt and grouting anchor cable at the roof, side and floor of typical roadway section. As can be seen from Figs. 11-12, within the monitoring time of 70 days, the forces of high-strength grouting bolt and grouting anchor cable both show a trend of gradual increase, and the anchorage member at the roof is stressed the most. For example, at 70d, the maximum force of high-strength grouting bolt is 122kN, and the maximum force of high-strength hollow grouting anchor cable is 268kN.

This indicates that after the new high-strength prestressed bolt-grouting and expansion repair scheme is adopted, the high-strength grouting slurry can effectively fill the on-site weak broken rock mass cracks and borehole pores in the free section, which can provide a stable anchorage foundation for the on-site high-strength grouting bolt (anchor cable). The support potential of high-strength grouting bolt (anchor cable) is released effectively. So that the rock mass and the anchorage support component s can form an effective cooperative bearing structure to jointly resist the external rock mass pressure, and then effectively limit the deformation and failure of rock mass.

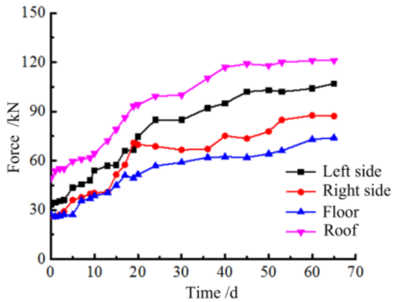


Figure 11. Typical monitoring curves of high-strength grouting bolts

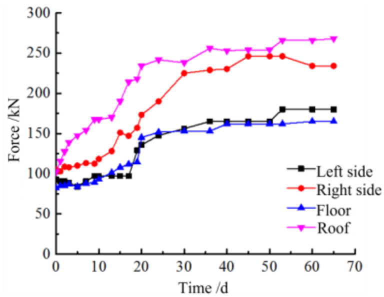


Figure 12. Typical monitoring curves of high-strength hollow grouting anchor cables

Fig. 13 lists the field roadway expansion and repair treatment effect after adopting the high-strength prestressed bolt-grouting and expansion support scheme. According to Fig. 13 and the above monitoring data, it can be seen that the roadway in the field has a good effect after expanding and repairing with this technology, and the spray layer is basically intact without obvious cracking and damage. Compared with the conventional bolt-mesh support and U-shaped steel arch support, the new technology can effectively enhance the self-bearing performance of weak broken rock mass and effectively limit the deformation and failure of rock mass, which has obvious advantages and effectiveness.

Figure 13. Repair effect of the field roadway

4. Conclusions

(1) Taking a typical roadway in soft and broken strata as an example, combined with the field geological conditions and the field test results, the large deformation and failure mechanism of the field roadway mainly includes three aspects. Firstly, the formation lithology is poor and the rock mass self-bearing capacity is low. Secondly, the stress concentration effect and the disturbance and destruction effect of recycling mining are significant. Thirdly, it is difficult to form an effective active cooperative bearing structure due to the unreasonable supporting method.

(2) Aiming at the problem of roadway rock mass control in weak broken strata, the technology of high-strength full-length prestressed bolt-grouting support with "high-strength support", "prestressed active support" and "full-length anchorage support" as the core are put forward. Key technologies such as new high-strength composite grouting bolt, high-strength hollow grouting anchor cable are developed.

(3) A new type of high-strength prestressed bolt-grouting is designed and applied successfully in the field. The monitoring results show that the maximum surface convergence deformation of rock mass is 56mm, the maximum stress of high-strength grouting bolt is 122kN, and the maximum stress of high-strength hollow grouting anchor cable is 268kN. Under the premise of ensuring the active supporting effect of rock mass prestress, the new high-strength prestressed bolt-grouting technology can effectively enhance the self-bearing capacity of soft and broken rock mass, give full play to the supporting potential of anchorage supporting component, and limit the deformation and failure of rock mass by using high-strength inorganic grouting materials to seal the cracks and boreholes in the free section of rock mass.

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References

[1]. WANG Hongtao. Study on failure mechanism of rock anchoring and bearing performances of prestress anchored surrounding rock[D]. Shandong University, 2015.

[2]. KANG Hong, WANG Jinhua. Rock bolting theory and complete technology for coal roadways[M]. Beijing: China Coal Industry Publishing House, 2007.

[3]. HOU Chaojiong, GOU Panfeng. Mechanism study on strength enhancement for the rocks surrounding roadway supported by bolt[J]. Chinese Journal of Rock Mechanics and Engineering, 2000, 19(3): 342-345.

[4]. LIU Quansheng, LEI Guangfeng, PENG Xingxin. Advance and review on the anchoring mechanism in deep fractured rock mass[J]. Chinese Journal of Rock Mechanics and Engineering, 2016, 35(02): 312-332.

[5]. KANG Hongpu, JIANG Tieming, GAO Fuqiang. Effect of pretensioned stress to rock bolting[J]. Journal of China Coal Society, 2007(07): 680-685.

[6]. Indraratna B, Kaiser P K. Analytical model for the design of grouted rock bolts[J]. International Journal for Numerical and Analytical Methods in Geomechanics, 1990, 14(4): 227-251.

[7]. Li C, Stillborg B. Analytical models for rock bolts[J]. International Journal of Rock Mechanics and Mining Sciences, 1999, 36(8): 1013-1029.

[8]. CAI Y，ESAKI T，JIANG Y. An analytical model to predict axial load in grouted rock bolt for soft rock tunnel-ling[J]. Tunnelling and Underground Space Technology，2004，19(6): 607-618.

[9]. Osgoui R R, Oreste P. Elasto-plastic analytical model for the design of grouted bolts in a Hoek–Brown medium[J]. International journal for numerical and analytical methods in geomechanics, 2010, 34(16): 1651-1686.
[10]. Bobet A, Einstein H H. Tunnel reinforcement with rockbolts[J]. Tunnelling and Underground Space Technology, 2011, 26(1): 100-123.
[11]. Wang Q, Qin Q, Jiang B, et al. Study and engineering application on the bolt-grouting reinforcement effect in underground engineering with fractured surrounding rock[J]. Tunnelling and Underground Space Technology, 2019, 84(FEB.):237-247.
[12]. He M C, Gong W L, Wang J, et al. Development of a novel energy-absorbing bolt with extraordinarily large elongation and constant resistance[J]. International Journal of Rock Mechanics & Mining Sciences, 2014, 67: 29-42.
[13]. Li C C. A new energy-absorbing bolt for rock support in high stress rock masses[J]. International Journal of Rock Mechanics and Mining Sciences, 2010, 47(3): 396-404.
[14]. KANG Hongpu, WANG Jinhua, LIN Jian. High pretensioned stress and intensive bolting system and its application in deep roadways[J]. Journal of China Coal Society, 2007(12): 1233-1238.
[15]. Li S, Wang H, Wang Q, et al. Failure mechanism of bolting support and high-strength bolt-grouting technology for deep and soft surrounding rock with high stress[J]. Journal of Central South University, 2016, 23(2): 440-448.
[16]. Wang H, Zheng P, Zhao W, et al. Application of a combined supporting technology with U-shaped steel support and anchor-grouting to surrounding soft rock reinforcement in roadway[J]. Journal of Central South University, 2018, 25(5): 1240-1250.
[17]. Yang S, Li M, Song G, et al. Optimization of face flexible bolting and grouting technology for longwall face support under difficult geological conditions[J]. Energy Science & Engineering, 2020, 8(4): 1260-1270.
[18]. Yang L, Jinpeng Z, Limin L. A new prestressed anchor-grouting reinforcement method for underground broken rock: a case study[J]. Arabian Journal of Geosciences, 2022, 15(6): 1-13.
[19]. WANG Qi, PAN Rui, LI Shucai, et al. Gob side entry failure mechanism and control of bolt-grouting in three soft coal seam[J]. Journal of China Coal Society, 2016, 41(05): 1111-1119.