Application of Bolter Miner Rapid Excavation Technology in Deep Underground Roadway in Inner Mongolia: A Case Study

Ma, Peng
Department of Earth Resources Engineering, Graduate School of Engineering, Kyushu University

Qian, Deyu
School of Mines, China University of Mining and Technology

Zhang, Nong
School of Mines, China University of Mining and Technology

Shimada, Hideki
Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University : Professor

他

https://hdl.handle.net/2324/4355069

出版情報：Sustainability. 12 (7), pp.2588-, 2020-03-25. MDPI
バージョン：

sustainability

MDPI

Article

Application of Bolter Miner Rapid Excavation Technology in Deep Underground Roadway in Inner Mongolia: A Case Study

Peng Ma [1], Deyu Qian [2,*], Nong Zhang [2], Hideki Shimada [1], Dongjiang Pan [3] and Kejun Huang [4]

1. Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University, Fukuoka 819-0395, Japan; ma18r@mine.kyushu-u.ac.jp (P.M.) shimada@mine.kyushu-u.ac.jp (H.S.)
2. School of Mines, China University of Mining and Technology, Xuzhou 221116, China; zhangnong@cumt.edu.cn
3. State Key Laboratory of Shield Machine and Boring Technology, China Railway Tunnel Group Co., Ltd., Zhengzhou 450001, China; pandongjiang@crecg.com
4. Shaanxi Coal and Chemical Technology Institute Company Limited, Xi'an 710070, China; huangkj@sxccti.com

* Correspondence: qian@cumt.edu.cn

Received: 04 March 2020; Accepted: 24 March 2020; Published: 25 March 2020

Abstract: Rapid excavation could mitigate the imbalance relationship between excavation speed and production needs that plays a pivotal role in the sustainable development of large underground coal mines. This paper provides a case study on Bolter Miner Rapid Excavation Technology (BMRET) in Menkeqing Coal Mine, which has a high production of 13 million tons per year in Inner Mongolia. The temporal characterization of excavation procedures is analyzed in detail based on field monitoring data. The improvement of the roadway driving process and efficiency under a new support design is introduced, and corresponding evaluation methods, including parallel operation index (P_x) and unit drilling-hole index (D_x), are proposed for BMRET. A field application is conducted to verify the effectiveness of the improved BMRET, which fully considers the structure characteristic of the bolter miner machine. The performance and reliability of this new support scheme are monitored in terms of roadway convergence and axial force of cable through professional instrumentation programs in the field. The results show that the average excavation speed of the BMRET is 36.15 m/day (1080 m/month), an increase of 99.72% compared with the original excavation technology, which indicates that the BMRET could provide high efficiency in roadway excavation and effectively control the stability of deep roadways. It is pivotal to apply BMRET to ensure sustainable and highly efficient coal production. This case study provides reference and guidance for rapid excavation of deep underground roadways with similar geological conditions.

Keywords: underground coal mine; deep roadway; rapid excavation; bolter miner; support efficiency

1. Introduction

The excavation speed of the roadways is a major concern in underground coal mines. With the mining depth increasing, the geological conditions of the surrounding rock become more and more complicated, and include large overburden and high tectonic stress, which necessitates the requirement for efficient roadway excavation and support systems in deep areas [1,2]. State-owned coal enterprises need to excavate new underground coal and coal-rock roadways up to 12,000 km per annum in China [3]. However, due to the low excavation speed, the number of roadway excavation faces in China is increasing rapidly [4]. High labor-intensity in tight spaces makes it difficult to catch up with the needs of production rate and also results in the occurrence of potential disasters [5]. Therefore, this clearly indicates that there is an urgent need to improve the excavation speed and efficiency of roadways by using rapid excavation technologies [6–8].

Roadway excavation speed is highly connected with the mechanization level of equipment, labor organization, and construction technology [9,10]. As of the current situation, 95% of coal seam roadways have been built by the comprehensive mechanized method in China. The mechanized equipment types are mainly categorized into three modes, listed below [11]:

(1) Boom-type road header in concert with a single jumbolter excavation system;
(2) Continuous miner coordinating with the bolting jumbo excavation system;
(3) Bolter miner rapid excavation technology (BMRET).

However, existing boom-type road headers and continuous miners are limited in roadway advancement due to bolting limitations. Since the mid-1980s, with the increasing demand for intelligent and automated technology, the drivage method of underground roadways has gradually switched away from roadheaders to continuous miners and, more recently, to machines with the characteristics of high performing development systems, especially with board roof and rib bolting equipment [12,13]. The bolter miner is a new type of underground roadway drivage machinery, with the functions of cutting and anchoring, which has been rapidly promoted and widely used worldwide for rectangular bolted roadways since the first bolter miner, ABM2, was put into action at Tahmoor Colliery in Australia in 1991 [14].

As an advanced technology, bolter miner driving technology has been used predominantly for high output and productivity in deep, highly stressed underground coal mines, especially for gateroad development [13]. The core feature of this technology is the integration of the functions of excavating, loading, transporting, and supporting, which improve workplaces and simplify the drivage process. The machine design considers safety and operational requirements; therefore, it is also used for rapid excavation in tough and restricted roadway conditions in deep underground coal mines [11]. At present, the field application of bolter miners is mainly in countries and regions such as Australia, the United States, Europe, and China. In detail, the number of bolter miners in China accounts for about one-third of the global total, and they have been gradually applied in deep roadways.

According to the literature review, the BMRET is mainly used to keep pace with rapidly increasing longwall productivity in Australia [15]. It was introduced to U.S. coal mines in the late 1990s, and the "top speed" was an advance of 388 feet (118 m) per shift due to the geological conditions in the U.S. mines, which allowed a less dense bolting pattern [7]. Later, the BMRET was introduced to Europe, and some improvements of this system were adapted for the local mining conditions, mainly including the early installation of high strength lockbolts and the use of design based on measurement for bolting patterns. The mines in Europe are generally deep and highly stressed; thus, more attention was paid to the support system performance of the bolter miner [14]. For instance, Daw Mill Mine has successfully operated bolter miners (the Joy 12BM15) in relatively difficult strata conditions with a buried depth of around 700–800 m, and a new support pattern involving 48 m of drilling for every 0.8 m advance was designed based on a computer model and realized the drivage rates at a cycle time of around 40 minutes and advance rates of 6 to 7 m/day. Similarly, Riccall Mine has achieved drivage rates over 125 meters per week under the depth of working in the Stanley Main Seam, varying from 750 to 850 m. In addition, Mogk. E. introduced an application case study of the Bolter Miner from Joy Mining Machinery Co., in combination with the self-advancing walking tail end at the Walsum colliery, with a daily distance of around 8.3 m. Another case report about the bolter miner technique in Europe was at Auguste Victoria mine, which achieved a high performance of 22 m/day after an improvement of the logistics and a major reduction in the manual operations. The situation of BMRET in China has been of interest in recent years. China's record of the maximum daily distance is 102 m, created in Daliuta coal mine by using a bolter miner speedy drivage system with a buried depth of 180 m [16] . However, the Daliuta coal mine is relatively shallow and has a simple geological condition. The driving speed of BMRET in China's deep roadways is around 15–25 m/day [17].

Based on the aforementioned background, BMRET has largely improved the efficiency, reduced cost, and been more operationally friendly for roadway excavation. Nevertheless, similar to the situation in the United States and Europe, under different mine and geological conditions in China, the advance rates and excavation efficiency of the BMRET show obvious fluctuations and differences. Over the past two decades, numerous research studies on optimizing the structural design of the bolter miner and its engineering performance to further improve its ergonomics and efficiency have been conducted by researchers worldwide. From the perspective of driving efficiency, the research on the bolter miner mainly includes the following aspects:

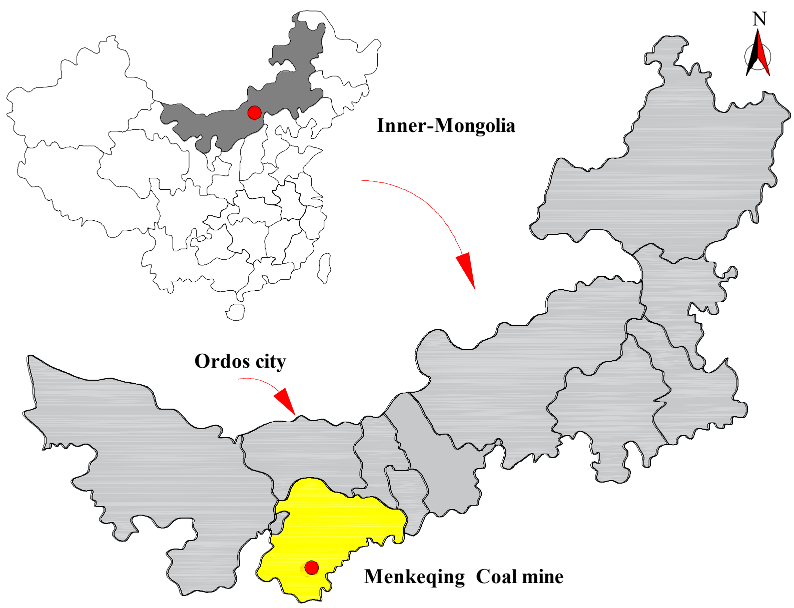
(1) The improvement of the effectiveness of the cutter drum and optimization of the rock breaking efficiency of the cutting system, including the arrangement of the cutting drum and the wear of the cutter [18];
(2) The digitization and intelligent transformation of the controlling system of the bolter miner to improve flexibility and maneuverability [19,20];
(3) The optimization of the structure layout of the machine's frame to realize the parallel operation of driving and supporting [21,22].

Therefore, there is a serious shortage of discussions on the coordinated and effective support system of BMRET, both of which highly restrict the roadway driving speed and utilization rate of the bolter miner. In particular, there is a lack of research on the synchronous and coordinated operation between the supporting system and the cutting system, which leads to the low efficiency of the BMRET in deep coal seam roadways. Thus, research on improving its efficiency and excavation speed is critically meaningful. This paper analyzes the temporal characterization of excavation procedures under the bolter miner driving system, introduces the improvement of roadway driving efficiency with a new support design, and proposes two new indicators for speed evaluation. A field application was conducted to verify the effectiveness of the improved BMRET.

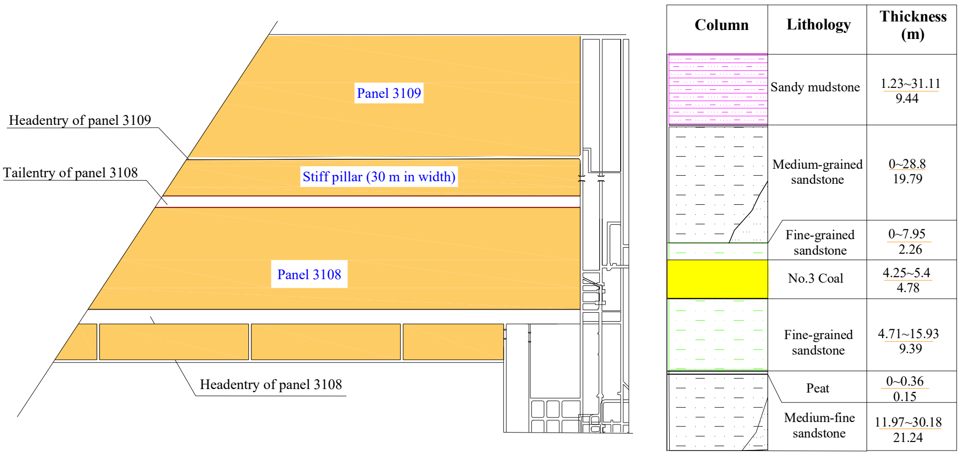
2. Engineering Geological Conditions

2.1. Geological conditions

Menkeqing coal mine, as shown in Figure 1a, located in the northeastern Ordos Basin and producing over 13 million tons annually using the longwall mining method, is a typical large modern underground coal mine and is located in a huge coalfield.



(**a**)



(b) (c)

Figure 1. General situation of Menkeqing Coal Mine and the tail entry of panel 3108. (a) Geographic location of Menkeqing Coal Mine, (b) Plan view of the local panel layout, (c) Stratigraphy of the test roadway.

Coal seam No.3 is the main recoverable seam, with an average inclination of around 3 and an average thickness of 4.78 m. The tail entry of panel 3108 (shown in Fig 1b) is the key transportation and ventilation route for this mining panel, with a burial depth of 720–750 m. The stratigraphy of the entry, which was investigated by the core logging method in an adjacent area, is shown as Fig 1c. The immediate roof of coal seam No.3 is a fine-grained argillaceous sandstone layer with an average thickness of 2.26 m, above which is the main roof of the target entry, composed of medium-grained sandstone. The entry designed as a rectangular section has a net width of 5.4 m and a net height of 3.6 m. It is excavated along the coal seam floor and retains about 1.2 m of coal as the immediate roadway roof; thus, two ribs and the roof are composed of coal. The roadway excavation and support design are closely related to the in-situ stresses and geological structure, and in this research, there is no obvious geological structure belt, so the influence of tectonic stress on the excavation process has not been considered. The in-situ stresses of coal seam No.3 were measured with the hydraulic fracturing method, and the results are shown in Table 1. Because of the deep buried depth, the in-situ stress of this roadway is generally large as a whole, and the horizontal principal stress is the dominant stress with an angle of 22.7° away from the roadway axis. Therefore, it can be concluded that, during roadway excavation, there will be large stress release and readjustment at the excavation face area; therefore, there will be higher requirements on the timing and scheme of roadway supporting.

Table 1. The in-situ stress of coal seam No.3.

Stress (Mpa)	σ_1	σ_2	σ_3	Azimuth angle (°)
	27.5	16.8	21.4	N22.7W

2.2. Original supporting design

The original support system of the entry was a combined system consisting of rockbolt, mesh, cable, and steel ladder. The support parameters are shown in Figure 2.

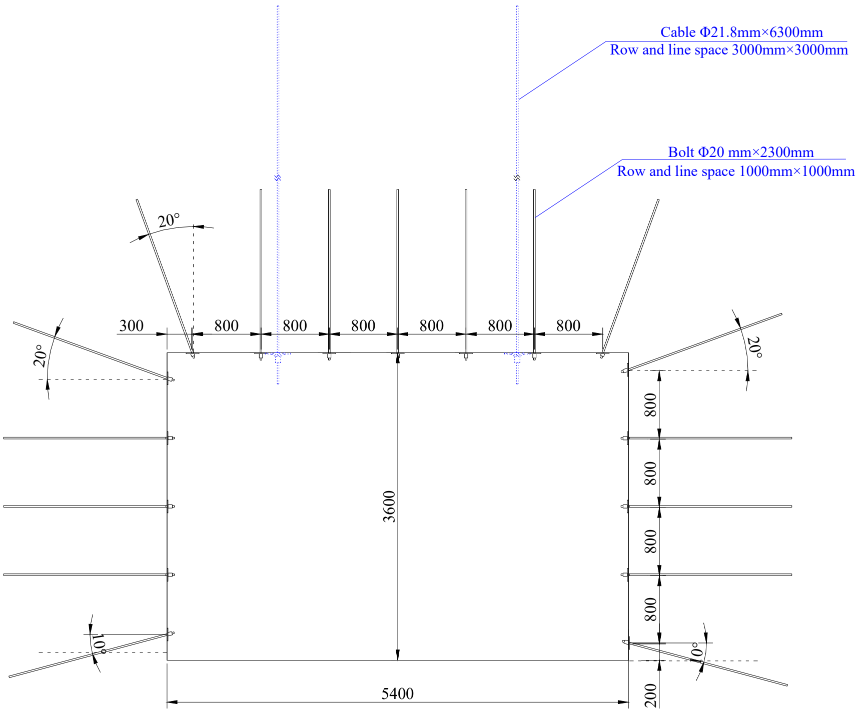


Figure 2. Original support scheme of the tail entry of panel 3108.

All rock bolts and cable bolts were partially grouted with resin cartridges; the parameters are listed in Table 2. The roof was supported by rock bolts and cable bolts. The diameter and length of the bolts were 20 mm and 2300 mm, respectively, with a spacing of 1000×1000 mm. The length of the anchorage zone of the bolts was 1000 mm with a pre-tightening force of at least 50 kN. The cable bolts were Φ17.8×6300 mm with a spacing of 3000×2400 mm. The pre-tightening force was 100 kN. Bar-mat reinforcement was used in the roof support. The dimensions of the single-layer bar-mat were Φ6.5×5400×1100 mm, combined with a 5400 m long steel ladder that was installed on the roof surface. The sidewall was supported by the rock bolts, with a spacing of 800×1000 mm, and the specifications were the same with the roof bolts.

Table 2. Parameters of the rebar and each cable bolt.

Type of bolt	Bolt length (m)	Grout length (m)	Diameter (mm)	Tensile strength (kN)
Rock bolts 2.3		1.0	20	50
Cable bolts 6.3		2.3	17.8	100

2.3. Development method and excavation process

The entry was excavated by the bolter miner MB670 (Figure 3), which was manufactured by Sandvik Mining Group. It is equipped with a hydraulic sliding frame with a 5.2 m-long horizontal cutting drum in front to cut forward, and the slide frame allows the cutting system to have a longitudinal movement of 1.0 m relative to the machine body. It has four roof bolting rigs and two rib bolting rigs integrated on the main frame, which can operate independently. The quantity of bolting rigs installed on the bolter miner is strictly limited by the narrow space and the compact structure of the machine, and the typical design for bolt miners is installed with four roof bolter rigs and two rib bolter rigs to avoid the interference between various procedures during the excavation.

The main processes of a typical operating cycle include the following steps:

(1) Coal-cutting: The cutting procedure was conducted by the cutting drum with a good rock breaking performance. The coefficient of hardness of No.3 coal seam was 1.8; therefore, the cutting process was simple and fast;
(2) Coal-transportation: During the MB670 cutting, the collecting head of this machine collected the dropped coal and loaded it into the middle conveyor, which then conveyed the coal to the receiving hopper of the trackless rubber-wheeled vehicle at the back of the MB670. Finally, the coal was transported to the channel belt machine to complete the transportation process, which could easily meet the transportation requirements and did not affect the operation of the bolter miner;
(3) Roadway shoring: The supporting procedures were conducted by the bolter rigs. However, the original support scheme was a high-intensity support system.

The detailed procedures of the tunneling process are introduced in the next section.

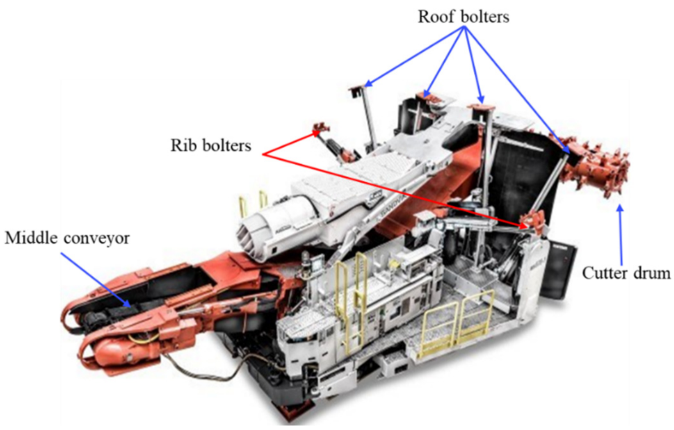


Figure 3. Schematic diagram of bolter miner machine excavation system (modified from Sandvik).

3. Procedures of BMRET, speed restriction and evaluation

3.1. Temporal characterization of BMRET procedures

Time consumption of procedures within a unit cycle is a key factor that influences the speed of the whole process of roadway excavation. In general, a particular sequence and the links between each excavation procedure in a unit excavation cycle are relatively fixed in order to facilitate operation and proficiency. According to the on-site investigation in the tail entry of panel 3108, the originally used excavation process of BMRET is shown in Figure 4. The time consumption of each procedure was tracked and monitored during the excavation process, as shown in Table 3.

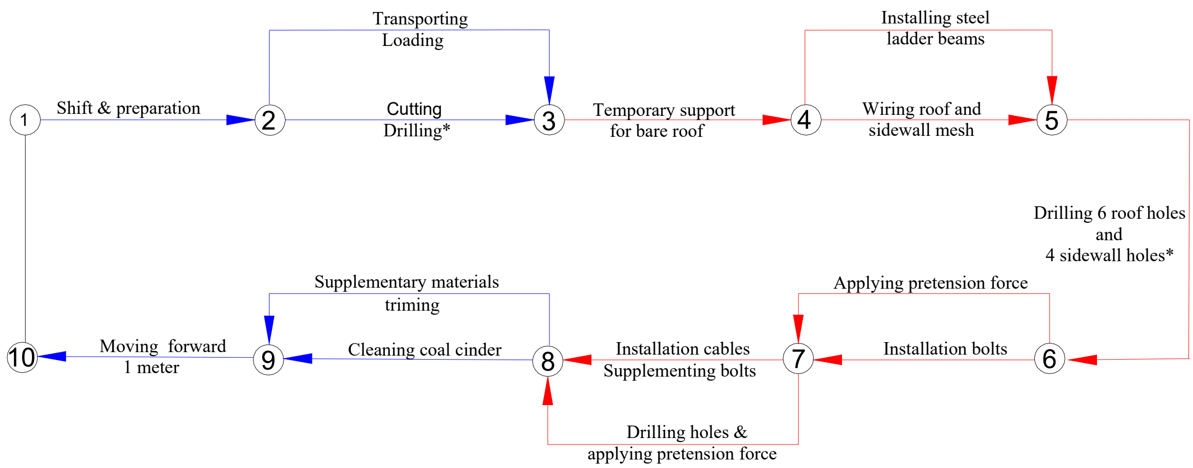


Figure 4. Schematic diagram of excavation technology process of bolter miner rapid excavation technology (BMRET).

Table 3. Average time consumption statistics of procedures.

No.	Working procedures	Procedures time consumption (min)	Real-time consumption under parallel operation condition (min)
1	Cutting 1 m ahead	9.5	9.5
2	Loading and transporting	9.5	
3	Moving forward 1 m	1.3	1.3
4	Wiring mesh	5.2	5.2
5	Installing steel ladder beams	1.1	
6	Temporary support	0.5	0.5
7	Drilling seven holes for roof bolts	8.6	8.6
8	Drilling four holes for rib bolts	3.5	
9	Installation bolts	6.3	6.3
10	Applying pretension force	2.2	2.2
11	Receding 0.5 m	0.5	0.5
12	Drilling two cable holes	6.7	6.7
13	Installing two cables	4.5	4.5
14	Applying pretension force	1.6	1.6
15	Trimming and cleaning	1.3	1.3
16	Supplementary materials	1.0	
	In total	63.3	48.2

Based on the above data, the average time consumption of a unit excavation cycle (cutting 1 meter forward) is 48.2 minutes, including 16 different procedures. In fact, in the process of excavation, cutting is the first step, and most of the time is dedicated to procedures related to support installation for the stability of the surrounding rock. In detail, the cutting time is 9.5 minutes, accounting for 19.71%. In contrast, the time used for supporting is 35.6 minutes, accounting for 73.86%. In order to specify the main time-consuming procedures in a unit excavation cycle, the procedures that took more than 5 minutes were analyzed, which include coal cutting, overlapping steel mesh, bolt drilling and installation, and cable drilling and installation. The time proportion of each procedure in a single cycle is shown in Figure 5.

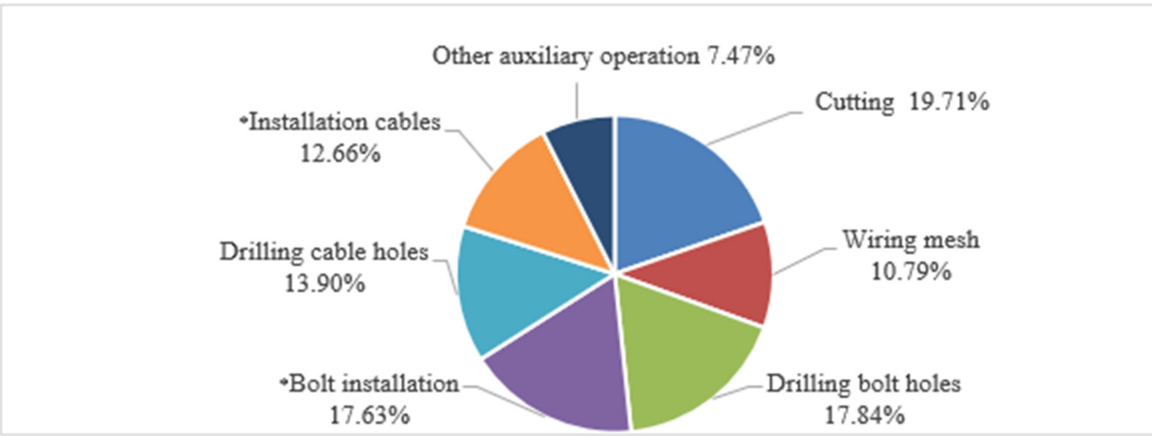


Figure 5. The time consumption proportion in a unit cycle.

It can be seen that, in the whole excavation cycle, the time consumption of six procedures accounts for more than 92.53% of the whole time. Except for cutting, the remaining five procedures are all related to the roadway supporting procedures, which means the cutting capacity of the bolter miner is idle for 80.29% of the working time. Consequently, the supporting system is the main factor restricting the excavation speed, and optimizing the support scheme and reducing the time consumption of supporting are effective strategies for achieving rapid excavation.

The detailed procedures for installing the bolts and cables highly constrain the support speed. The main support procedures in a unit excavation cycle included drilling and installing, on average, 17 rock bolts and 0.67 cable bolts and wiring a steel mesh and a steel ladder. Thus, there exists a serious imbalance between supporting requirement and the supporting capacity of the bolter miner. However, due to the existence of parallel operation, a unit excavation cycle saves 15.1 minutes. It is suggested that optimizing and coordinating procedures to realize simultaneous operation is an effective way to achieve rapid excavation. Actually, parallel operation procedures, especially the more time-consuming procedures, are still few in the current excavation process because of the uncoordinated capabilities of current BMRET between cutting and supporting. Thus, the support procedures and parallel operation of BMRET need to be highly valued and studied.

3.2. New proposed evaluation indicators

It is necessary to propose scientific indicators for quantitative evaluation of excavation speed and efficiency. From analyzing the current widely used speed evaluation indicators in underground roadway, there is a shortage of accurate indicators for rapid excavation evaluation, especially for the causal relationship between roadway support procedures and driving speed. Common indicators to evaluate the excavation speed mainly include the speed (including day speed and month speed), distance of excavation cycle, and worker efficiency [11,23].

The aforementioned indicators are mainly suitable for the evaluation of overall excavation technology from a macro perspective, which easily leads to superficial evaluation of the excavation speed. It is difficult to interpret the intrinsic relationship between the excavation speed and each procedure during the roadway excavation. Thus, new evaluation indicators are necessary for the organization of the working procedures along with quantitative methods for evaluating support efficiency in the excavation process. This paper proposes and defines two new indicators to scientifically quantify the excavation speed and the relationship between the main influencing factors for BMRET rapid excavation.

(1) Parallel operation index (P_x)

The concept of parallel operation index is proposed to evaluate the degree of collaborative operation of each excavation cycle. The parallel operation index, P_x, is defined as the ratio of the saved time by the parallel operation procedures to the sum of the total cycle time in a single excavation cycle:

$$P_x = (T_P/T_W) \times 100\% \tag{1}$$

where T_P is the time saved by the parallel operation and T_W is the sum of actual time consumption in the whole unit excavation cycle.

Parallel operation index is an indicator used to quantify the effect of parallel operation. A high value of this index indicates that many procedures are being done at the same time and that there is a high efficiency of time utilization in the unit excavation cycle. This new indicator is a simple way to quantify the procedures' organizational efficiency.

(2) Unit drilling-hole index (D_x)

The workload of rock bolts and cable installation is obviously associated with roadway excavation speed, but the relationship between them has not yet been quantified. In order to evaluate the influence of the installation density of bolts and cables on the excavation speed, the concept of unit drilling-hole index, D_x , is suggested, which refers to the average length of holes needed to drill for every meter of the roadway:

$$D_x = L_H/L_E \tag{2}$$

where L_H is the total length of boreholes drilled for rock bolts and cables in a unit cycle and L_E is the length of a unit excavation cycle.

The bolt–cable combined supporting system exerts the function of strengthening rock mass by drilling holes in the rock mass. Thus, the length of the drilling can accurately represent the number of rock bolts and cables installed and also directly reflect the support density and time consumption of the support schemes. The unit drilling-hole index not only reflects the efficiency under different supporting schemes but also establishes the connection between supporting workload and excavation speed. Thus, the unit drilling-hole index is an effective parameter to evaluate the efficiency and speed of different supporting schemes. According to the definition, the unit drilling-hole index of the conventional bolt and cable combined support system was derived as follows.

$$L_H = (L_{1R} \times n_{1R} + L_{2R} \times n_{2R}) + (L_{1W} \times n_{1W} + L_{2W} \times n_{2W}) + (L'_{1W} \times n'_{1W} + L'_{2W} \times n'_{2W}) \quad (3)$$

where L_{1R} is the length of the drilling hole for a roof bolt; n_{1R} is the number of roof bolts; L_{2R} is the length of the drilling hole for a roof cable; n_{2R} is the number of roof cables; L_{1W} is the length of the drilling hole for a bolt of one sidewall; n_{1W} is the number of bolts for one sidewall; L_{2W} is the length of the drilling hole for a sidewall cable; n_{2W} is the number of cables for one sidewall; L'_{1W} is the length of the drilling hole of a bolt for the other sidewall; n'_{1W} is the number of bolts for the other sidewall; L'_{2W} is the length of the drilling hole for a cable of the other sidewall; n'_{2W} is the number of cables for the other sidewall; and L_E = 1 meter.

4. New support scheme design and engineering practice

4.1. New support design

A new roadway support system is proposed based on the features of the BMRET. It is known that a large number of support schemes have been put forward for deep roadway conditions, including yieldable steel arch support in Germany, a combined support scheme of bolts and cables in China, and various cable and bolt trusses with high pretension in America [3,4,9,24]. However, these schemes lack consideration of the time-sensitivity of support procedures, performance of the key equipment, and coordination of the integral excavation system. The mainstream bolter miners in the market and mine sites were investigated, including Sandvik Mining and Construction Co., Ltd., Joy Mining Machinery Co., Ltd., Dosco Co., Ltd, and other companies. Based on the above background, and fully considering the time consumption of each procedure in a unit excavation cycle, a time-based and rapid support scheme is proposed and applied with medium–short high prestressed cables. The scheme of the new support system is shown in Figure 6.

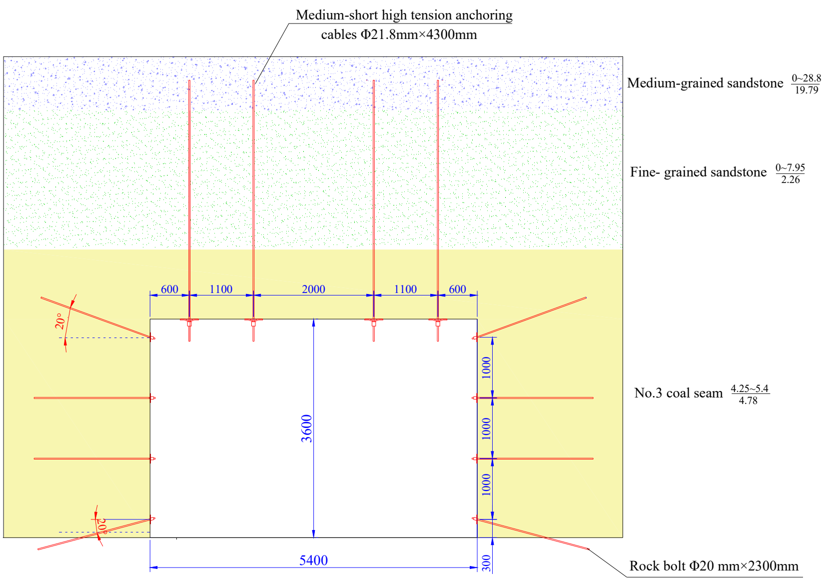


Figure 6. Schematic diagram of new support system applied in the tail entry of panel 3108.

The key features of this new optimal support scheme are shown in the following:

(1) Simple and efficient roof support scheme.

The roof of the entry is controlled and strengthened by four medium–short high prestressed cables matched with large-sized pallets (see Figure 7).

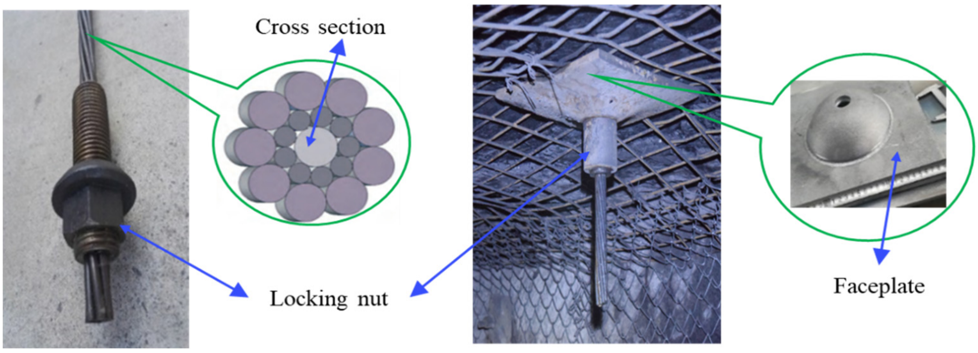


Figure. 7 Schematic diagram of medium–short high prestressed cable. (Strength σp: ≥1600 MPa; Specification: Φ22~25 mm L3.0~6.0 m; Tension stress: 590 kN; Spacing: 1.4~2.0 m pallets: ≥ 0.09 m^2).

The number of medium–short cables is consistent with the number of roof bolter rigs. The purpose of this design is to try to balance the time consumption of cutting and supporting and to try to realize the parallel operation of cutting and supporting. In addition, the rock bolts and other steel ladders for roof support are all eliminated, which greatly simplifies the supporting procedures and reduces the time consumption of roof supporting. The medium–short high prestressed cable is made of 19 high strength steel stands with a diameter of 21.8 mm and a broken load of 600 kN. The length of this cable is required to be 4~6 m; in this way it can be fully tensioned and effectively stretched, so that the roof convergence can be effectively restrained. Compared with the traditional cable, its strength and elongation are increased by 100%, and it not only has the characteristics of a cable but also exerts the function of a rock bolt. The large-sized pallets are required to be greater than 0.09 m^2 in order to effectively diffuse the pretension of an anchor cable to the roof rock.

(2) High pretension force system.

The applied pretension force for each medium–short high prestressed cable is over 200 kN; therefore, the free end of the high-tension cable is in a state of elastic stretch, which generates a high pressure on the roof to restrain the settlement. Additionally, the pretension force for bolts is required to be up to 80 kN, both for roof and rib bolts. High pretension force is an effective way to improve the bolting effectiveness.

(3) Immediate support.

Since the cutting and supporting procedures are carried out simultaneously, this new support system realizes the possibility of immediate support. The free deformation time of the newly excavated roadway section is controlled within a short time (within 10 minutes), which can inhibit the early subsidence of the roof and restore the rock mass to the equilibrium state as soon as possible. The rib support in the new system is designed dynamically according to the excavation speed of the roadway, leaving space for the adjustment and release of surrounding rock stress and ensuring safety as well as excavation speed.

4.2. New BMRET and Field application

After adopting this new support system, the optimal BMRET was named the new BMRET. In order to validate and further interpret this new excavation system, the reliability and effects were verified by a case study. The time consumption of the procedures of the excavation cycle and distance were monitored. Finally, the evaluation was carried out with new indicators, and the results were compared with the original plan. Procedures in a unit excavation cycle have been simplified under the new support system due to the balanced cutting and supporting capacities. Based on the onsite monitoring, the excavation process of this new BMRET is shown as Figure 8.

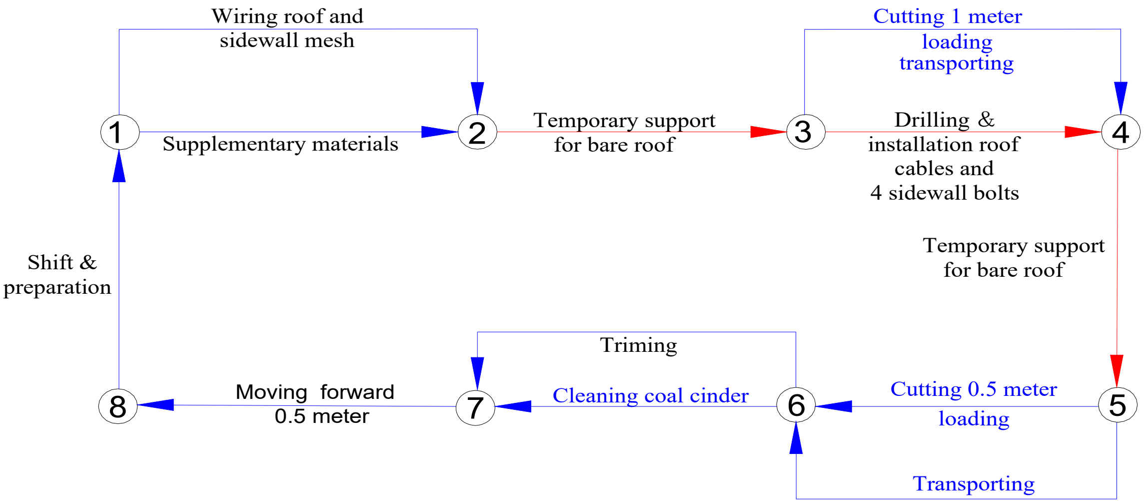


Figure. 8 Schematic diagram of excavation process of new BMRET.

Compared with the original system, the number of parallel procedures was obviously increased, which can exert the functions of the bolter miner. In the course of site excavation, the time consumption of each excavation procedure was carefully monitored by tracking two working shifts for over one month (see Table 4). With a cycle distance of 1500 mm, the average time consumption of a unit excavation cycle is 22.7 minutes. Compared to the original scheme, the time saved by this new BMRET is 24 minutes from the perspective of cycle time consumption.

Under this new technology, the three-shift working system was adopted, with two shifts for excavation and one for maintenance, the same as the original system. The distance achievable with this new system within 20 days is shown in Table 5.

Table 4. Time consumption of new excavation system.

No.	Working procedures	Average time consumption (min)	Real-time consumption under parallel operation condition (min)
1	Moving forward 1 meter	1.3	1.3
2	Temporary support for bare roof	0.5	0.5
3	Wiring mesh for roof and ribs	4.5	4.5
4	Supplementary materials	4.5	
5	Cutting 1 meter ahead	9.5	
	Loading and transporting	9.5	
6	Drilling four holes for roof cable	4.9	10.1
7	Drilling four holes for rib bolts	3.6	
8	Installation of bolts and cables (including pretension)	5.2	
10	Moving forward 1 meter	1.3	1.3
11	Temporary support	0.5	0.5
12	Cutting 0.5 meter ahead	4.5	4.5
13	Loading and transporting	4.5	
In total	-	45.8	22.7

Table 5. Distance monitoring of the original scheme.

Date	Distance of morning shift (m)	Distance of maintenance shift (m)	Distance of evening shift (m)	Day distance (m)
2017.9.7	19.5	1.5	18	39
2017.9.8	19.5	1.5	19.5	40.5
2017.9.9	21	3	22.5	46.5
2107.9.10	21	1.5	21	43.5
2017.9.11	19.5	1.5	16.5	37.5
2017.9.12	15	0	15	30
2017.9.13	19.5	0	21	40.5
2017.9.14	16.5	3	24	43.5
2017.9.15	25.5	0	19.5	45
2017.9.16	19.5	1.5	18	39
2017.9.17	19.5	3	9	31.5
2017.9.18	9	0	19.5	28.5
2017.9.19	0	0	15	15
2017.9.20	19.5	0	0	19.5
2017.9.21	22.5	4.5	19.5	46.5
2017.9.22	21	0	15	36
2017.9.23	21	0	19.5	40.5
2017.9.24	16.5	0	19.5	36
2017.9.25	21	0	18	39
2017.9.26	13.5	0	12	25.5
Average	18	1.05	17.1	36.15
In total	360	21	342	723

The average excavation speed is 36.15 m/day and 1080 m/month under the new BMRET. Compared with the original system, the excavation speed of this new technology increases by 99.72%.

(1) The parallel operation index of new BMRET

The parallel operation index was calculated in order to assess the organizational efficiency and time utilization efficiency of the new BMRET. According to the data of the on-site time monitoring, 23.1 minutes is saved, and actual time consumption in a total excavation cycle is 22.7 minutes. Thus, the final parallel operation index is:

$$P_{Xn} = \frac{\mathrm{T}_p}{T_W} \times 100\% = 23.1/22.7 \times 100\% = 101.76\%$$

Under the new excavation technology, the parallel operation index reaches 101.76%. This means that the time saved by parallel operation exceeds the real-time consumption of a unit excavation cycle, and the efficiency of time utilization is improved 69% compared with the original system.

(2) Unit drilling-hole index

The essence of the new support is one type of rock bolt-cable combined support system. Accordingly, the unit drilling-hole index can effectively evaluate the support efficiency and density of this new system. Within a distance of 1500 mm, four high strength medium–short cables were installed on the roof, and eight rock bolts were installed in two sidewalls. Hence, the unit drilling-hole index of the new system can be calculated by Eq. (2) and Eq. (3):

$$D_x = \frac{(L_{2R} \times n_{2R}) + (L_{1W} \times n_{1W}) + (L'_{1W} \times n'_{1W})}{L_E} = 22.40$$

As a result, the unit drilling-hole index of the new BMRET is 22.40, which means the length needed to drill holes for excavation 1 meter forward is 22.40 m. Compared to the original system, the length of the drilling holes has been reduced by 19 m and 45.89% in the new BMRET for every 1 meter distance. Furthermore, the time consumption for the support procedures decreases significantly due to the workload of drilling and installation being reduced greatly. Thereby, the efficiency of the time utilization of the entire system has obviously improved.

4.3. Results and Discussion

The mechanisms associated with the new support scheme are elaborated by means of numerical simulation from another publication. The reliability of this new supporting system has been confirmed in similar case studies [17,23]. In this study, the support effectiveness of the new support scheme was analyzed by some accurate field measurement methods. The roadway convergence, the axial force of the high strength medium–short cables, and fracture development in the roof of the roadway under the new BMRET were monitored. Three kinds of monitoring equipment were mainly used at this site, namely, a hand-held laser range finder for the surface displacement of the roadway, borehole scanners for fracture development in the surrounding rock, and digital dynamometers to monitor the axial force of the cable. Figure 9 shows the monitoring and schemes in the field for a distance of 150 m (from 1600 to 1750 m in roadway 3108).

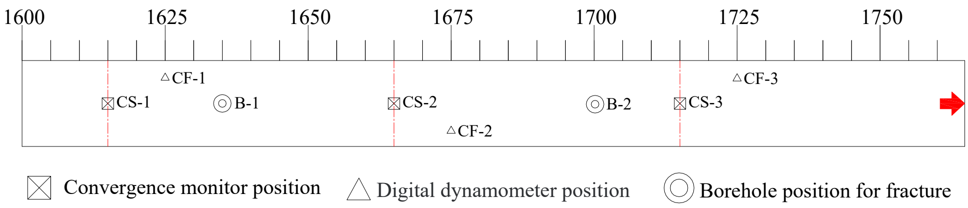


Figure. 9 Schematic diagram of field monitoring scheme.

The convergence of the roadway can reflect the relative displacement and stability of the inner part of the rock mass. The adaptability of support schemes to the rock mass can be effectively evaluated from this perspective. The intersection point method was applied to measure the convergence of the roadway section, including roof subsidence and two-side convergence, and three monitoring sites were chosen as observation sections to record the variation of roadway convergence after the implementation of the new supporting scheme. The results are shown in Figure 10 and Figure 11.

According to the monitoring data, the maximum displacement of the roof is 17 mm, and the average subsidence is 13.7 mm. The maximum convergence of sidewalls is 24 mm with an average value of 23 mm. This demonstrates that the whole convergence of the roadway is quite low.

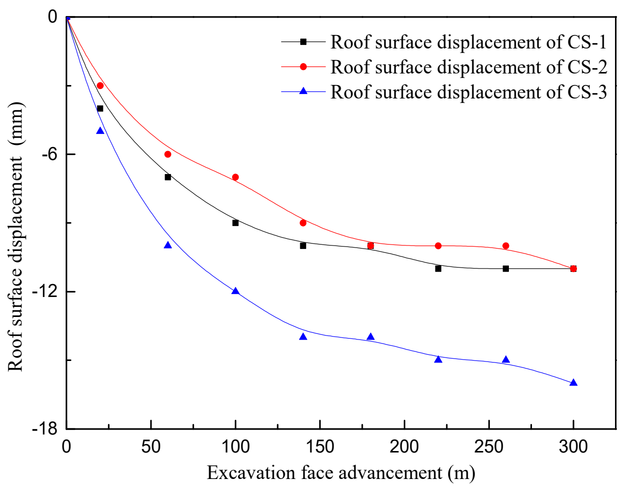


Figure. 10 Relationship between roof surface displacement and excavation face advancement.

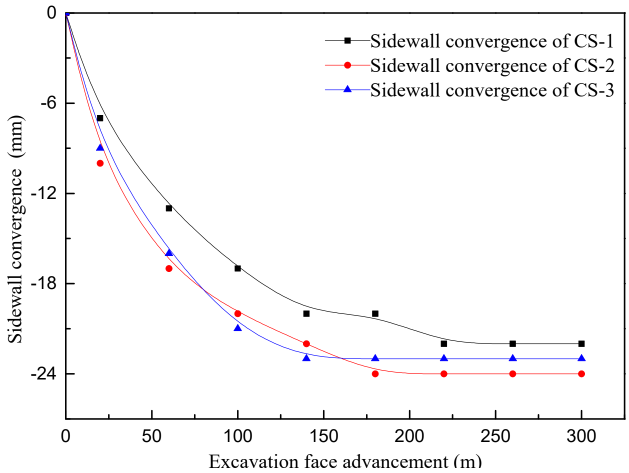


Figure.11 Relationship between sidewall convergence and excavation face advancement.

The axial load of the prestressed cables was monitored to evaluate their working state. In the field test, digital dynamometers were used as sensors to monitor the axial force. After cable installation, the axial load was measured over time. Monitoring results are as shown in Figure 12.

From the monitoring results, the axial load of the cable is up to 220 kN after stabilization. The axial load of the medium–short high prestressed cable first increases after installation, then gradually becomes stable. To be specific, within 10 hours after installation, the axial load of the cable changes drastically, then growth tends to be moderate, and it becomes stable after 80 hours with a value up to 220 kN. The final state of the cable is tense due to it being subjected to a higher workload, which is beneficial in maintaining the stability of the surrounding rock. Additionally, the high load bearing state is also conductive to exerting the supporting performance of the cable.

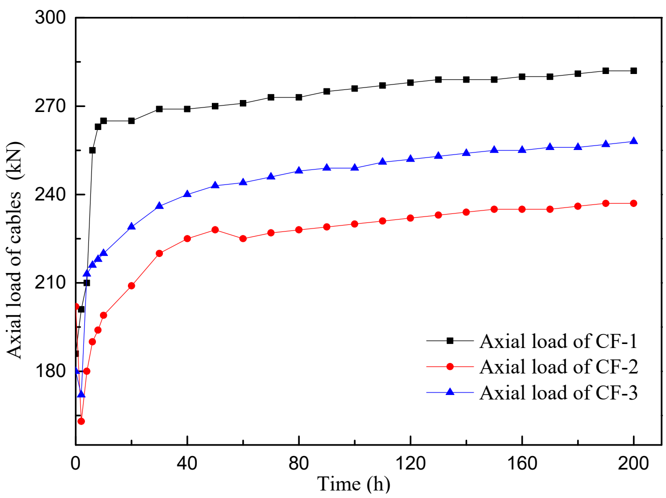


Figure.12 Relationship between axial force of cable and time (within 200 h).

Borehole image monitoring of the roof fracture development was carried out to confirm the rock mass condition. By monitoring the rock mass discontinuity and internal fracture development, the reliability of the support scheme can also be effectively evaluated. In this research, the surrounding rock was monitored by a ZKXG30 borehole scanner, which can show the fracture distribution and development trend within 10 m of rock mass by an endoscope head. The fracture images are shown in Figure 13.

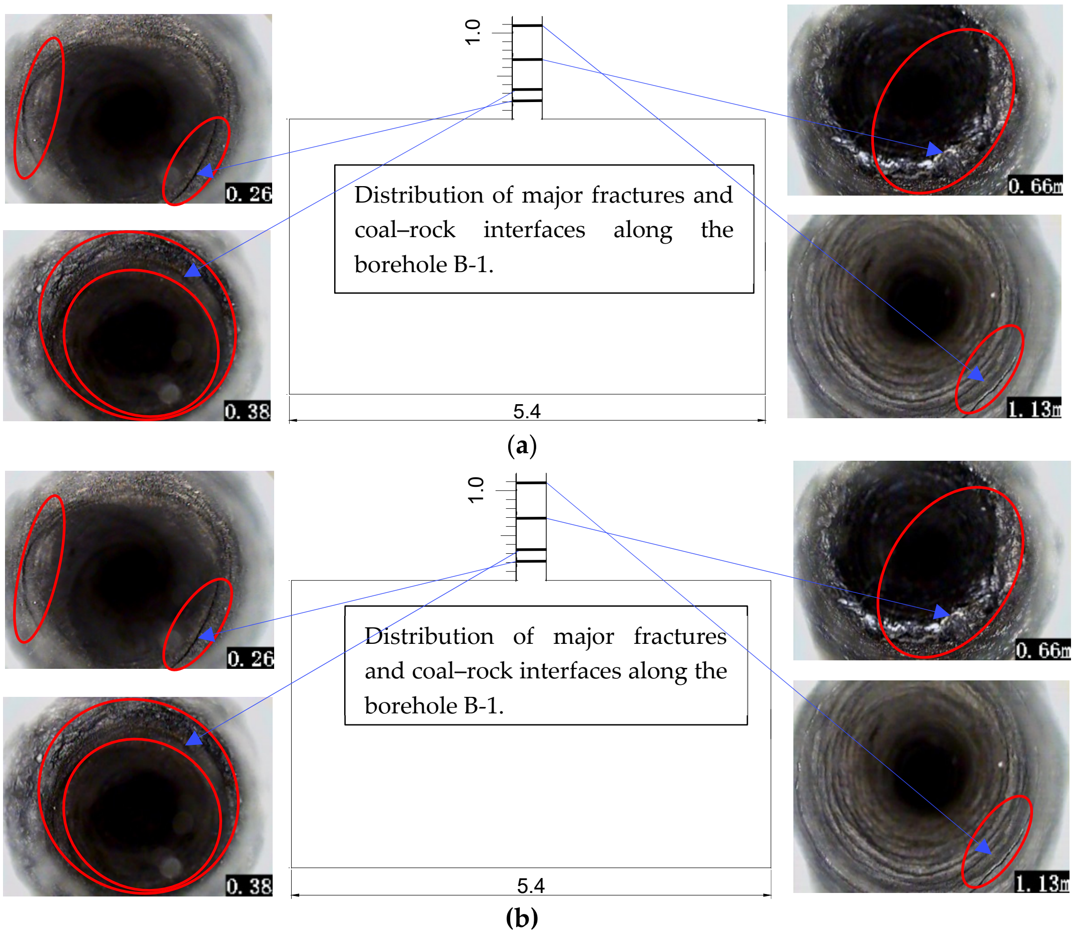


Figure 13. Fracture development of roadway roof; (a) B-1; (b) B-2 (Unit: m).

According to the results of borehole image monitoring, the separation and fracture development in the rock mass is in the range of 1.27 m from the roof surface. Fractures were only observed in the shallow depth and coal–rock interface of the roadway roof. The largest fracture opening is within 2 mm. There is no visible fracture development in the rock mass above 1.27 m. Therefore, based on the roadway monitoring results, the use status and effect of the new BMRET, and through the scientific comparison of the two systems before and after, it is concluded that the new technology has a good overall controlling effect on the surrounding rock of the entry.

5. Conclusions

In order to resolve the technical difficulties of the existing bolt-cable combined support system for BMRET, new indicators for efficiency evaluation and a new support system for rapid excavation are proposed. With the application of the new BMRET, the excavation speed of the tail entry of panel 3108 has been significantly improved, and it can provide a reference for mines under similar geological conditions. The research results were obtained from field measurements and engineering practices, which provide practical reference and guidance for other coal mines with similar geological conditions. Some conclusions are summarized as follows:

(1) The main constraints for current BMRET include the high density of supporting schemes and the uncoordinated procedure organization of the excavation process. In detail, the time used for supporting accounts for 73.86% in a unit excavation cycle.

(2) The parallel operation index (P_X) and the unit drilling-hole index (D_x) are proposed for efficiency evaluation. The parallel operation index is for evaluating the procedures' organization in the excavation process, and the unit drilling-hole index is for quantifying the effectiveness of the

support schemes from the perspective of excavation speed. Both new indicators have been applied and proved to be feasible.

(3) Considering the characteristics of the bolter miner, new BMRET is put forward that uses a new support scheme. A case study was carried out in a large cross-section of roadway in China. The average excavation speed under this new BMRET is 36.15 m/day and 1080 m/month. Compared with the original excavation technology, the excavation speed increased by 99.72%. The parallel operation index improved from 32.76% to 101.76%, increasing by 79%. The unit drilling-hole index was reduced from 41.4 to 22.4, decreasing by 45.89%. The monthly distance and the daily distance were more than 1000 m and 45 m, respectively, which amounts to the fastest speed under the same geological condition in China.

Author Contributions: All of the authors contributed extensively to the work. P.M. and D.Q. proposed key ideas. P.M. conducted the field measurements and wrote the manuscript. D.Q. afforded the financial support for the project leading to this publication. D.Q., N.Z., H.S., D.P, and K.H. modified the manuscript.

Funding: This work was financially supported by the National Natural Science Foundation of China (Grant No. 51704277), the High-level Innovation and Entrepreneurship Talents Introduction Program of Jiangsu Province of China, the Natural Science Fundamental Research Program Enterprise United Fund of Shaanxi Province of China (Grant No. 2019JLZ-04), the Fundamental Research Funds for the Central Universities (Grant No. 2018QNA27), and the State Scholarship Fund from the China Scholarship Council.

Acknowledgments: The authors would like to express appreciation to the staff at the Menkeqing Coal Mine for their assistance during the field measurements.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

P_x	the parallel operation index
T_P	the time saved by the parallel operation
T_W	the sum of actual time consumption in a unit excavation cycle
D_x	the Unit drilling-hole index
L_H	the total length of boreholes drilled for rock bolts and cables in a unit cycle
L_E	the length of a unit excavation cycle
L_{1R}	the length of drilling hole for a roof bolt
n_{1R}	the number of roof bolts
L_{2R}	the length of drilling hole for a roof cable
n_{2R}	the number of roof cables
L_{1W}	the length of drilling hole of a bolt of one sidewall
n_{1W}	the number of bolts of one sidewall
L_{2W}	the length of drilling hole for a sidewall cable
n_{2W}	the number of cables of one sidewall
L'_{1W}	the length of drilling hole of a bolt of the other sidewall
n'_{1W}	the number of bolts of the other sidewall
L'_{2W}	the length of drilling hole for a cable of the other sidewall
n'_{2W}	the number of cables of the other sidewall

References

1. Fairhurst, C. Some challenges of deep mining. *Engineering* **2017**, *3*, 527–537.
2. Kumar, A.; Waclawik, P.; Singh, R.; Ram, S.; Korbel, J. Performance of a coal pillar at deeper cover: Field and simulation studies. *Int. J. Rock Mech. Min*. Sci. **2019**, *113*, 322–332.

3. Kang, H.P.; Lin, J.; Fan, M.J. Investigation on support pattern of a coal mine roadway within soft rocks—A case study. *Int. J. Coal Geol.* **2015**, *140*, 31–40.
4. Kang, H. Support technologies for deep and complex roadways in underground coal mines: A review. *Int. J. Coal Sci. Technol*. **2014**, *1*, 261–277.
5. Xie, H.; Gao, M.; Zhang, R.; Xu, H.; Wang, Y.; Deng, J. The subversive idea and its key technical prospect on underground ecological city and ecosystem. *Chin. J. Rock Mech. Eng*. **2017**, *36*, 1301–1313.
6. Wang, Y.B.; Shan, R.L.; Cai, W.L.; Wang, H.; Yang, S.J.; Xu, C. Factor analysis on factors influencing on driving speed of coal roadway in Xishan mining area. *J. China Coal Soc*. **2011**, *36*, 925–929.
7. Liu, X.; Kong, D.; Song, G. Study on the rapid excavation technology of deep large cross-section rock tunnel. *Proj. Mine Disaster Prev. Control* **2014**, 133–137.
8. Yu-, W. MB670-type bolting machine for roadway express excavation. *China Acad. J. Electron. Publ. House*. **2013**, *11*, 15–17.
9. Jiao, Y.Y.; Song, L.; Wang, X.Z. Improvement of the U-shaped steel sets for supporting the roadways in loose thick coal seam. *Int. J. Rock Mech. Min. Sci.* **2013**, *60*, 19–25.
10. Wang, C. The optimal support intensity for coal mine roadway tunnels in soft rocks. *Int. J. Rock Mech. Min. Sci*. **2000**, *37*, 1155–1160.
11. Chen, J.S.; Gao, M.Z. Research on integration of roadway excavation, bolting, support, and detection. *Procedia Eng*. **2011**, *26*, 869–875.
12. Qiao, S. Performance evaluation of different pick layouts on bolter miner cutting head. *J. Min. Sci*. **2018**, *54*, 969–978.
13. Bertignoll, H.; Saria, W.; Owens, K. Slow cutting for higher productivity and safety—The sandvik bolter miner MB610. *Coal Int.* **2014**, *262*, 34–37.
14. Leeming, J.; Flook, S.; Altounyan, P. Bolter miners for longwall development. *Coal International Mining and Quarry World*. **2001**, *249*, 179–182.
15. Bertignoll, I.H. The Alpine Bolter Miner—Austrian technology for rapid roadway development. *Min. Technol.* **1995**, *77*, 163–165.
16. Gao, D.; Liu, Y.; Luo, W. The application of speedy drivage system in daliuta coal mine. *IOP Conf. Ser. Mater. Sci. Eng*. **2019**, *490*, 62–73.
17. Xie, Z.; Zhang, N.; Feng, X.; Liang, D.; Wei, Q.; Weng, M. Investigation on the evolution and control of surrounding rock fracture under different supporting conditions in deep roadway during excavation period. *Int. J. Rock Mech. Min. Sci*. **2019**, *123*, 104–122.
18. Qiao, S.; Wang, A.L.; Xia, Y.M.; Liu, Z.Z.; Liu, J.S.; Yang, M. Influence of pick layouts on the performance of bolter miner cutting head. *Min. Sci.* **2018**, *25*, 161–174.
19. Baldwin, J. Innovation in roof bolted development roadways-the Voest Alpine ADM 20 continuous miner bolter. *CIM Bull*. 1996, 40-45.
20. Puhakka, T.; Tamrock, S.; Coetzee, J. System integration and operational reliability in tele-operated mining. *Coal Int*. **2001**, *249*, 226–228.
21. Dongbao, Z. Development status and key technology of intelligent rapid driving technology in coal seam roadway. *Coal Eng.* **2001**, *50*, 6–9.
22. Graham, M.W.J. Developments and trends in miners/bolters. *Int. J. Rock Mech. Min. Sci. Geomech.* **1996**, *1*, 31A–32A.
23. Xie, Z.; Zhang, N.; Qian, D.; Han, C.; An, Y.; Wang, Y. Rapid excavation and stability control of deep roadways for an underground coal mine with high production in inner Mongolia. *Sustainability*. **2018**, *10*, 1160.
24. Kang, Y.; Liu, Q.; Gong, G.; Wang, H. Application of a combined support system to the weak floor reinforcement in deep underground coal mine. *Int. J. Rock Mech. Min. Sci.* **2014**, *71*, 143–150.