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Study on the improvement of the open TBM system and supporting equipment based on the Gaojiapu Coal Mine

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In order to cope with multi-dimensional mine disasters in deep mines, enhance the adaptability of the open tunnel-boring machine (TBM) to the actual mine working face environment, and improve the excavation speed of the open TBM, based on the excavation project of Gaojiapu Coal Mine in Zhengtong Coal Industry, Shaanxi Province, this paper comprehensively considers the difficulties encountered by the TBM in the excavation process and improves the open TBM system and its supporting equipment. The research shows that removing the redundant system and supporting equipment of the open TBM can effectively solve the difficulties of the TBM entering the mine, such as loading and unloading, and turning; optimizing the open TBM shield, shortening the main beam, and setting the support platform and jumbolter system on the main beam can deal with the problem that the TBM support is not timely and easy to jam. Opening circular holes and installing slag cleaning guide plates on the main beam of the open TBM can timely clean up the waste slag on the main beam and protect the main beam from deformation. Installing a slag cleaning bucket wheel machine between the main beam of the open TBM and the trailer can reduce the accumulation of waste slag on the road ahead. Compared with ordinary excavation construction technology, the monthly average footage level of the open TBM after technical improvement is 300.88 m, which is 3.8 times that of the rock roadway general excavation and 1.6 times that of the rock roadway comprehensive excavation.

KEYWORDS

open TBM, supporting equipment, complex geology, roadway excavation, goaf

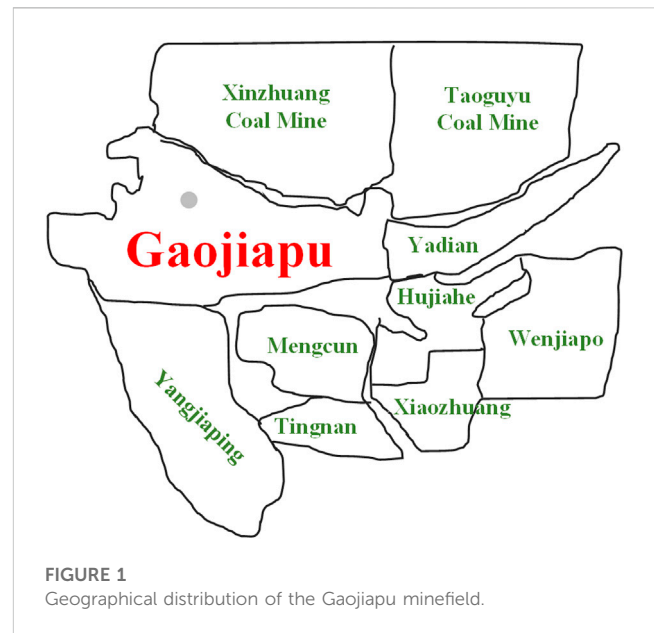
1 Introduction

With the decrease in the shallow coal seam, coal mining has begun to move to deep mining (Chun et al., 2023) and the mine environment will certainly become more complex. The environment of the deep roadway excavation face is very complex, has high ground pressure (Fan et al., 2019) (Liang et al., 2022) (Fan et al., 2020a), high ground temperature (Zhang et al., 2017), high gas (Fan et al., 2020b), high confined water (Guo et al., 2019), and soft rock, and other disasters are full of roadway. The traditional roadway excavation construction technology has not been well qualified for the excavation work under complex geological conditions in deep mines (Yuan and Zhang, 2023). The excavation construction technology of the mining industry needs to

be reformed, and advanced intelligent equipment should be introduced to replace the old piece of equipment to improve the excavation speed and ensure production progress.

Because the tunnel boring machine (TBM) has the advantages of high work efficiency (Wu et al., 2021a), strong applicability (Wei et al., 2019), strong safety and reliability (Wen et al., 2022), and good roadway forming, it is widely used in railways, subways, and other industries. The traditional excavation construction technology is very slow in the complex geological roadway, which causes tension in the follow-up work of the mine and seriously affects the economic benefits of the enterprise. In recent years, there have been more and more research studies on the TBM. He et al. (2013) proposed that the adaptability of the TBM to roadway should be improved according to the surrounding rock conditions and TBM models after comparing different roadway excavation construction technologies. Tan et al. (2022) proposed 11 evaluation indexes for TBM tunneling adaptability combined with the actual conditions of the tunnel and optimized the evaluation indexes. Zhang et al. (2022) used the Bi-GRU-ATT model to study the prediction of TBM tunnel parameters, and the research shows that the model can help the TBM to make intelligent decision analysis. Wu et al. (2021b) proposed a method of mutual feedback perception between TBM equipment and the surrounding rock by using the deep neural network (DNN) combined with tunnel surrounding rock parameters. Mao et al. (2015) developed a new type of TBM automatic positioning control system, which can solve the problems of low accuracy, complex operation, and time consumption of the previous TBM control system. Du et al. (2022) not only simplified the installation of TBM disc props but also developed a manipulator to assist in replacing props, which reduced the labor intensity of TBM maintenance personnel and improved the safety factors of underground work. He et al. (2022) developed a new TBM slag removal robot for cleaning the waste slag at the bottom of the tunnel, which can effectively remove the waste slag at the bottom of the open TBM.

So far, research studies on the TBM mainly focus on the adaptability evaluation of the excavation face, tunnel model prediction, and other operations. There are few studies on the improvement of the TBM system and its supporting equipment (Sun et al., 2018). Therefore, based on the working environment of the Gaojiapu Coal Mine in the Zhengtong Coal Industry of Shaanxi Province, this paper will study the technical improvement of the open TBM system and supporting equipment so that the open TBM can better adapt to the environment of the Gaojiapu Coal Mine excavation face and improve the efficiency of excavation work. In addition, the open TBM construction causes less disturbance to the surrounding rock and can form a neat roadway section, which is conducive to the future use of underground mine empty areas to build oil and gas storage (Qiu et al., 2023) (Zhang et al., 2023) (Qiu et al., 2022) (Fan et al., 2016) (Wang et al., 2023) (Chen et al., 2020) (Zhao et al., 2023) (Fan et al., 2020c). Finally, by comparing the excavation workload generated by different excavation construction techniques in the Gaojiapu Coal Mine, the advantages of using the improved open TBM are objectively evaluated. It provides a new solution for mines with poor geological conditions and low excavation-construction efficiency such as Gaojiapu, and also accumulates valuable experience for the application of the TBM in deep mine multi-coupling disaster mines.



2 Project overview and TBM technical problems

2.1 Project overview

The Gaojiapu Coal Mine of the Zhengtong Coal Industry in Shaanxi Province is located in the northwest of the Binchang mining area, and the detailed location distribution is shown in Figure 1. The area of the Gaojiapu Coal Mine is 219 km², the buried depth of the mine is 1,000–1,100 m, the coal reserves are 974 million tons, and the service life is expected to be 62.5 years. The roadway developed in the Gaojiapu Coal Mine comprises mainly four rock roadways in the east and west areas, respectively. The total amount of roadway development is 31,800 m, and 4,870 m have been completed. The remaining work tasks are very heavy. Due to the influence of mine geological conditions, roadway excavation construction technology, and mine disasters, the excavation progress of the Gaojiapu Mine is very slow, and subsequent production work of the mine is seriously affected. According to the current mine production situation, if the construction technology of ordinary comprehensive excavation and blasting excavation is adopted, the Gaojiapu Mine will have a one-sided production situation of up to 1 year, when the working faces of the fourth and fifth plates are connected. Coal production will be reduced by about 1.5 million tons. Therefore, improving the speed of roadway excavation has become a key factor to solve the problem of tight production connection in the Gaojiapu Mine. The TBM has the advantages of fast excavation speed, high safety factor, and good roadway forming capability (Xie et al., 2023; Liu et al., 2023; Yang et al., 2023; Wang et al., 2020; Wang et al., 2022), which can solve the current technical problems in the Gaojiapu Mine. After full investigation and technical demonstration, combined with the actual working conditions of the roadway excavation face, the open TBM was finally selected as the new piece of roadway excavation equipment to solve the problems of slow roadway excavation speed and tight mine production connection in the Gaojiapu Coal Mine.

2.2 TBM technical problems

The Gaojiapu Coal Mine has the characteristics of complex geological conditions and multiple coupling of disasters. The following problems need to be considered when using the open TBM in this mine.

- (1) The roadway space is limited, and the open TBM has problems such as difficult entry, difficult loading and unloading, and difficult turning.

The Gaojiapu Coal Mine has the characteristics of large coal seam depth, small roadway section, and limited roadway space. In addition, the size of the auxiliary shaft cage in the Gaojiapu Coal Mine is 5.8 m long, 2.5 m wide, and 3.8 m high. The maximum lifting load of the cage is only 37 t. The size of the flat car in the roadway of the mine is 4.5 m long and 1.8 m wide, and the maximum bearing capacity is only 40 t. Because the existing open TBM systems and their supporting equipment have the disadvantages of large size, weight, and turning radius, and high difficulty in loading and unloading in the mine, it is not suitable for direct use in the Gaojiapu Coal Mine. If it is put into the Gaojiapu Coal Mine without technical improvement, there will be problems such as difficult entry, difficult loading and unloading, and difficult turning. Therefore, in order to solve the aforementioned problems, it is necessary to simplify the existing open TBM system and supporting equipment in the market so that the open TBM can better adapt to the working environment of the Gaojiapu Coal Mine.

- (2) The lithology changes greatly, the roadway formation is poor, and the open TBM has problems such as untimely support and easy jamming.

The stratum structure of the Gaojiapu Coal Mine is complex and changeable. The open TBM excavation inevitably passes through soft strata such as sandstone, sandy mudstone, and coal seam. When the open TBM passes through the soft strata, due to the soft rock strata of the roof and floor of the roadway and the excessive deformation of the surrounding rock, it is prone to collapse accidents such as roof fall and spalling, which leads to open TBM jamming (Ding et al., 2022a; Fan et al., 2021; Chen et al., 2014; Ding et al., 2022b; Liu et al., 2019; Ma et al., 2022). In order to solve the problem of TBM jamming, the existing open TBM generally installs a shield device to reduce the TBM jamming problem through the protective effect of the shield. However, some of the existing shields cannot freely expand and contract, and other expansion ranges are limited, which cannot play a supporting role in time and effectively when the weak surrounding rock is broken. In addition, the existing support technology of the open TBM needs to be supported manually, which has the disadvantages of slow support speed and high risk (Song et al., 2023) (Chen et al., 2022). If the open TBM is not supported in time, it will seriously threaten the safety of staff and equipment. Therefore, the open TBM used in the Gaojiapu Coal Mine needs to have the functions of timely support and preventing equipment jamming.

- (3) The excavation distance of the roadway is long, the amount of waste slag is large, and the open TBM has the problem of untimely slag removal.

The roadway of the Gaojiapu Coal Mine was designed to have four main roadways in the east and west areas, respectively. The length of roadway development in the east area was 30,000 m, the length of roadway development in the west area was 31,800 m, and the length of the unexplored roadway in the east and west areas was 56,930 m. In summary, the Gaojiapu Coal Mine has the characteristics of long roadway distance, large excavation workload, and large amount of waste slag. However, the open TBM is comprehensive equipment that integrates multiple technologies and can quickly complete rock breaking, support, slag removal, and other operations. The amount of roadway development in the Gaojiapu Coal Mine is large, and the open TBM will produce a large amount of waste slag and congest the road during the construction process, resulting in the difficulty of the open TBM advancement. In addition, the Gaojiapu Mine has soft strata and the open TBM in the construction process will inevitably encounter roof fall, spalling, and other emergencies, making the waste slag directly fall on the main beam of the open TBM or through the finger shield gap to the main beam. As a result, the accumulation of waste slag in the inner cavity of the main beam affects the normal operation of the belt conveyor. In severe cases, it will squeeze the main beam to produce deformation and damage the main beam structure. Therefore, the open TBM used in the Gaojiapu Coal Mine must have the function of rapid slag removal; otherwise, a large amount of waste accumulation will inevitably affect the normal operation of the TBM.

3 Improvement of the open TBM system and supporting equipment

Usually the TBM consists of systems for excavation, support, slag discharge, ventilation, dust removal, anti-impact, explosion-proof, and other systems (Zhang et al., 2021) and is equipped with a cutterhead, main drive, shield, gripper, trailer, and other supporting equipment (Wang et al., 2014). Due to the complexity of the open TBM system and supporting equipment, it is easy to cause the disadvantages of large size, weight, and turning radius, which is not suitable for the Gaojiapu Coal Mine with a small roadway section and limited roadway space. Therefore, the Shaanxi Zhengtong Coal Industry is based on the existing open TBM; combined with the actual working environment of the Gaojiapu Mine, the existing open TBM is improved to better adapt to the actual working environment of the Gaojiapu Mine.

3.1 Streamlined open TBM system and supporting equipment

In order to solve the problems of difficult entry, difficult loading and unloading, and difficult turning of the open TBM, first, the open TBM system and supporting equipment were simplified, and then, the redundant rear-supporting trailer was removed. Only four trailers were retained, and each trailer was connected by the universal joint. The first trailer was equipped with automatic jumbolters to anchor the monorail suspension equipment, and the idle position could be used to stack materials; the second trailer was equipped with a cooler and dust collector; the third trailer was equipped with a dust collector, a fan, and a wind storage tube, and a position reserved for the auxiliary gripper. On both sides of the fourth trailer, jumbolters were installed as the bottom angle support rigs, which are responsible for 1–2 bolts

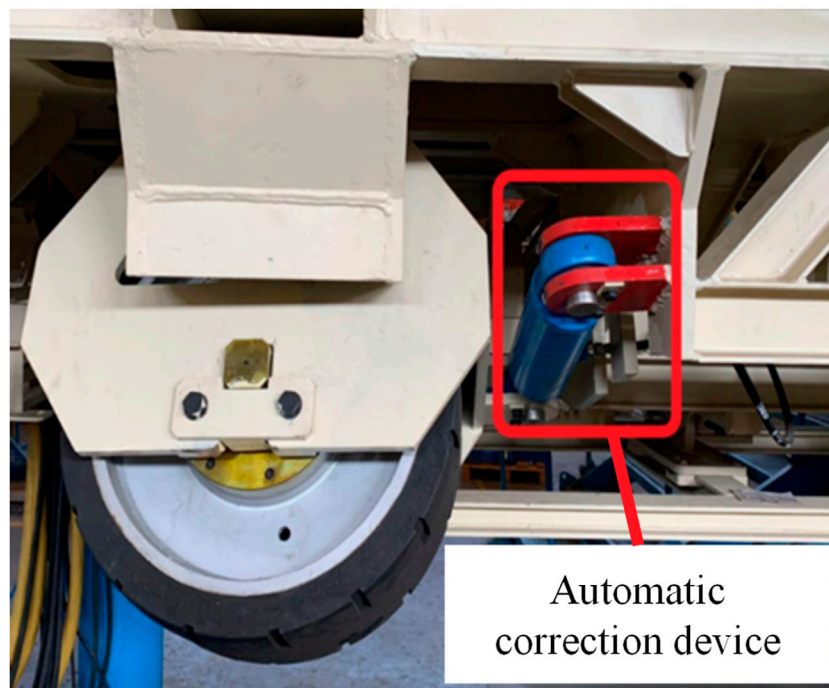


FIGURE 2 Automatic correction device.

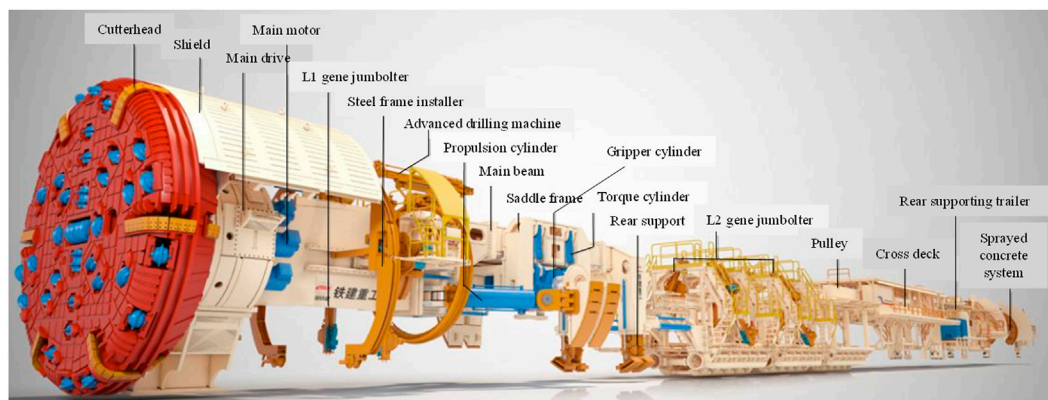


FIGURE 3 Unsimplified open TBM.

below the waist line. Second, according to the actual situation of the mine, the connection bridge and sprayed concrete system in the supporting equipment were canceled (practice found that it was not necessary). Third, an automatic correction device was added to the first wheel of each trailer (Figure 2). The automatic correction device can adjust the wheel direction of the trailer through the oil cylinder, thereby assisting the TBM to successfully complete the turning work. Finally, 15 suspension vehicles were equipped on the open TBM, and some supporting systems and equipment were suspended on the right monorail through the suspension vehicle. The size of each pulley was

determined according to the size of the cage. The assembly method of the pulley was relatively simple. It only needed to be hoisted to the monorail crane beam and then connected with the ball hinge, without the need for a cumbersome assembly and splicing. Each pulley was equipped with independent pipelines and cables, which could be quickly installed and evacuated by connecting pipelines and cables. This not only removes unnecessary devices in the open TBM system and the supporting equipment but also reduces the assembly difficulty of the TBM system and supporting equipment. It also greatly reduces the workload of the assembly chamber layout and saved the

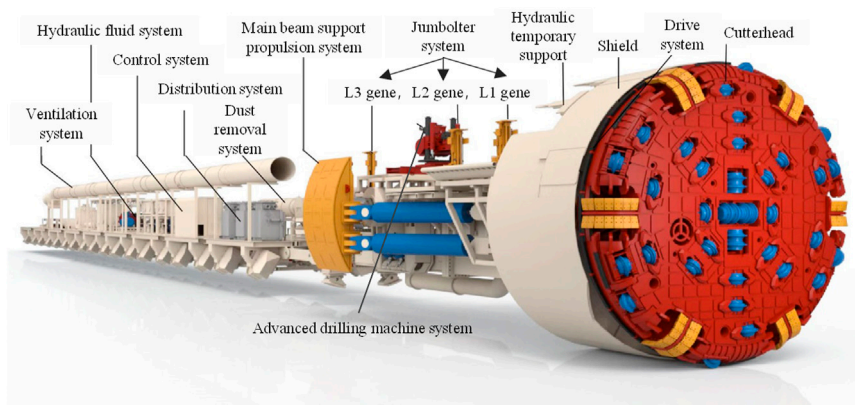


FIGURE 4
Simplified open TBM.



FIGURE 5
Shortened shield.

preparation time before the TBM work. Figures 3, 4 show the schematic diagrams of the open TBM system and supporting equipment before and after simplification. The total length of the unsimplified open TBM is 167 m, and the total length of the simplified open TBM is only 75 m.

3.2 Improved open TBM support system and supporting equipment

In order to solve the problems of untimely support and jamming of the open TBM shield when the surrounding rock is broken, first, the length of the shield connected to the

cutterhead was shortened (Figure 5), and then, the top part of the shield was replaced with a finger shield capable of secondary expansion (Figure 6). The finger shield can use the oil cylinder to expand up and down, to achieve the purpose of timely support, reducing TBM jamming and ensuring roof safety. Second, the main beam of the open TBM was shortened to 14 m, and a movable support platform was arranged on the upper part of the main beam (Figure 7), which is not only conducive to the support work of the open TBM but also reduces the turning radius of the TBM. The specific methods are as follows: a large support platform was set on the upper part of the main beam in front of the gripper. The large support platform was welded by multiple steel plates and steel frame structures, and the steel frame structure was bolted to both sides of the main beam 1 and fixed with the large support platform. A multi-level partition support platform was arranged on the upper part of the main beam behind the gripper. By setting up a large support platform and a multi-level partition support platform, it is convenient for workers to complete the support work on the support platform. A propulsion cylinder was arranged under the large support platform to push the support platform for displacement, and the maximum distance of the platform forward was 1.2 m. When the TBM is excavating, by promoting the support platform, the jumbolters on the platform were supported, and the two could work together to improve the support efficiency. Third, eight jumbolter systems were set up on the support platform of the open TBM main beam (Figure 8), and the encoder was arranged at the bottom of the jumbolter. In this way, it can not only support the top, shoulder, and two sides of the roadway synchronously and quickly to significantly improve the support efficiency of open TBM but also accurately control the jumbolter to support the bolt and anchor cable at the designated position of the roadway surrounding rock to effectively improve the safety factors of underground work. Finally, in order to save manpower and improve the safety factors of underground work, the jumbolter was installed at the bottom of the fourth trailer to support the bolt and anchor cable at the bottom of the roadway to increase the support strength of the roadway and improve its safety.

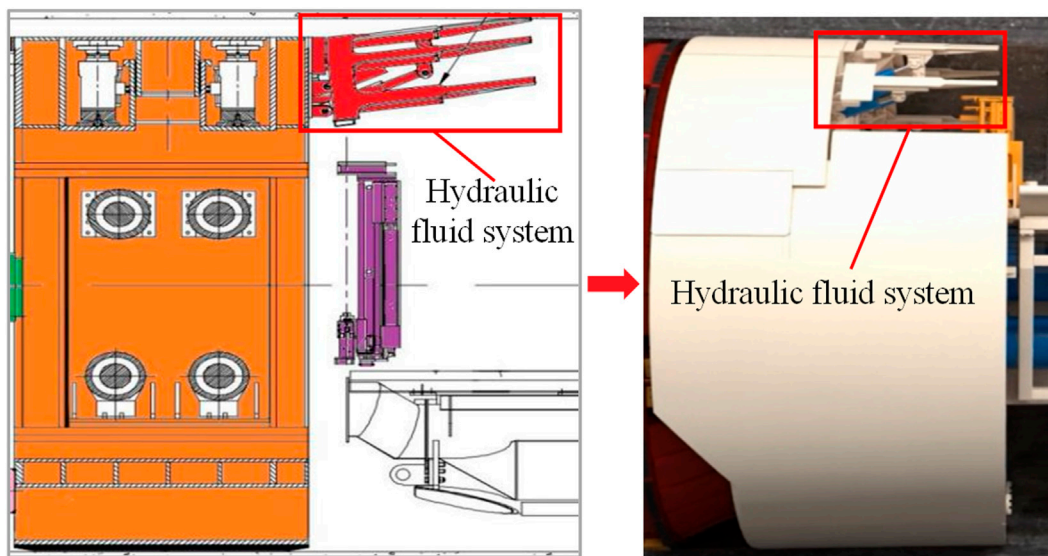


FIGURE 6
Scalable finger shield.

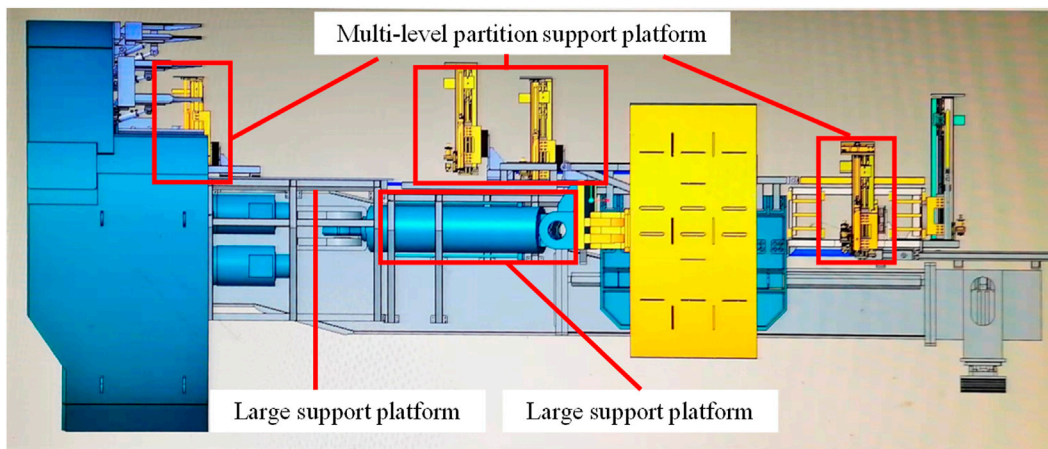


FIGURE 7
Supporting platform.

3.3 Improved open TBM slag discharge system and supporting equipment

In order to solve the problem of untimely cleaning of waste slag by the open TBM, first, a slag cleaning bucket wheel machine with a speed of 1r/min was set between the open TBM main beam and the first trailer (Figure 9), which is used to clean up the waste slag on the track in front of the trailer and transport it to the belt conveyor. The slag cleaning bucket wheel machine could be lifted by a lifting cylinder up to 300 mm. Second, the slag-skimming device was installed on the second wheel of the four trailers of the

TBM to further clean up the falling rocks on the road. Third, multiple circular holes were added to the main beam of the open TBM (Figure 10). The belt conveyor was directly below the circular holes to facilitate the timely cleaning of the waste slag. Each circular hole was equipped with a corresponding cover, which can be sealed when not in use to maintain the internal ventilation of the main beam. This not only facilitates the cleaning and maintenance of the internal equipment of the main beam but also reduces the weight of the main beam and saves the manpower and material resources consumed in the assembly. It can also stack materials on the circular holes after the upper cover

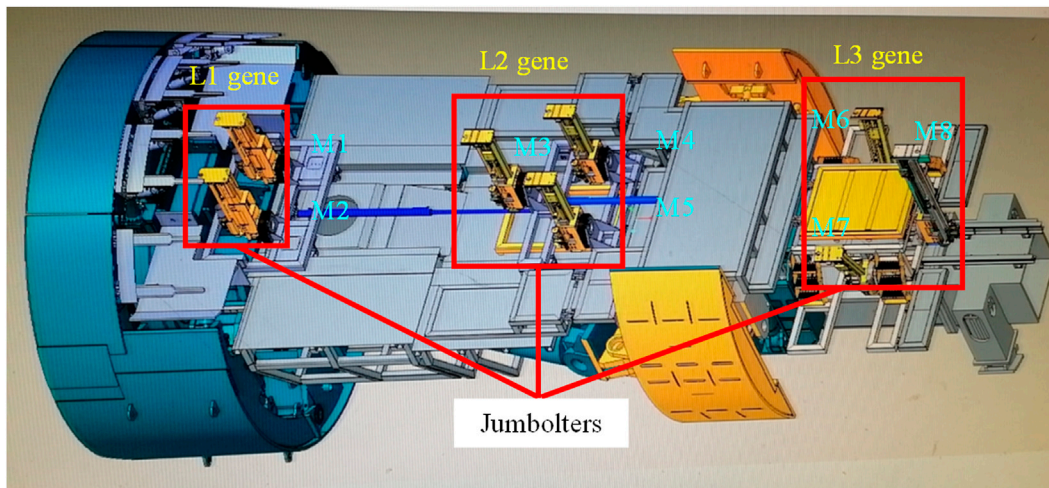


FIGURE 8
Jumbolter layout.



FIGURE 9
Slag cleaning bucket wheel machine.

of the main beam to improve the space utilization rate. The specific practices are as follows: [Figure 10](#) shows that the main beam was designed as a split structure, and the main beam 1 was connected to the main beam 2 by bolts. In order to solve the

problem of waste slag accumulation on the main beam, four circular holes 1–4 were arranged on the main beam 1, in which the circular holes 3 and 4 were located directly below the circular holes 1 and 2, respectively, and the main beam 1 was penetrated.

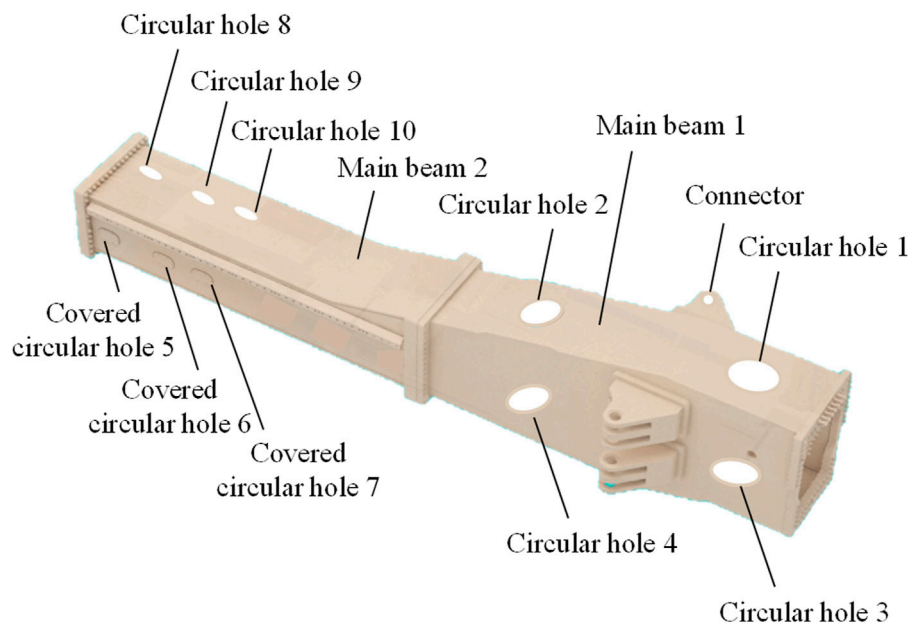


FIGURE 10
Main beam with circular holes.



FIGURE 11
Main beam reserved for the slag collecting port.

There were six circular holes 5–10 on the main beam 2, in which the circular holes 8–10 were located directly behind the circular holes 5–7, and the main beam 2 was penetrated. All circular holes

had corresponding covers, which were connected with circular holes by hinges. Figure 11 shows that circular holes 1 and 2 are used to collect automatically dropped waste slag or manually

TABLE 1 Footage level statistics of different excavation–construction technologies.

Construction technology	Excavation footage level/m								Total
	January	February	March	April	May	June	July	August	
A	71	73	62	116	107	46	0	0	475
B	72	0	146	258	232	282	245	106	1,341
C	265	140	305	263	222	170	415	627	2,407

A: rock roadway general excavation; B: rock roadway comprehensive excavation; C: open TBM.

clean the waste slag to the hole, and then let the waste slag pass through the main beam and fall on the belt from circular holes 3 and 4. In addition, the lower circular holes 3 and 4 can also be used to repair the equipment in the main beam and clean up the waste slag falling into the main beam. Side circular holes 5–10 are also used to repair the piece of equipment in the main beam and clean up the waste. Finally, a slag-cleaning guide plate device was set up on the upper part of the main beam of the open TBM, which can automatically collect the falling waste slag from the finger shield gap.

4 Engineering practice application effects

Table 1 is the statistical table of the footage level after different excavation–construction techniques are adopted in the Gaojiapu Coal Mine from January to August 2021. Table 1 shows that the total amount of the footage level of different tunneling construction technologies is in the order of the open TBM > rock roadway comprehensive excavation > rock roadway general excavation. According to the calculation of actual working months, it is found that the monthly average footage level of rock roadway general excavation and rock roadway comprehensive excavation is 79.17 m and 187.71 m, respectively. However, after the construction of the improved open TBM, the monthly average footage level is as high as 300.88 m. In addition, after further detailed calculation, it is found that the average daily footage levels of rock roadway general excavation and rock roadway comprehensive excavation are 2.62 m and 6.24 m, respectively, while the average daily footage level is 9.91 m after the improved open TBM construction. Compared with rock roadway general excavation and rock roadway comprehensive excavation, the monthly average footage level of the open TBM is nearly four times (3.8 times) and nearly two times (1.6 times) the construction speed of rock roadway general excavation and rock roadway comprehensive excavation, respectively. This shows that the improved open TBM in the Gaojiapu Coal Mine can adapt well to the environment of the roadway excavation face, significantly improve the excavation speed, and effectively alleviate the tension of production connection in the Gaojiapu Coal Mine. It also shows that improving the open

TBM according to the working conditions of the mining site is conducive to improving the adaptability of the open TBM to the environment of the roadway excavation face.

5 Conclusion

- (1) By removing the redundant rear-supporting trailer and installing the automatic correction device on the wheels of the remaining trailer, the problems of difficult entry, difficult loading and unloading, and difficult turning of the open TBM can be solved.
- (2) By improving the open TBM shield, shortening the main beam and arranging the mobile support platform on the main beam, and then setting the anchor jumbolter system on the support platform, the problems of untimely support and easy jamming of the open TBM can be solved.
- (3) By opening circular holes on the main beam of the open TBM, installing a slag-cleaning guide plate, and adding a slag-cleaning bucket wheel machine between the main beam and the trailer, the problem of untimely slag cleaning of the open TBM can be solved.
- (4) Compared with the ordinary excavation construction technology, the improved open TBM can well adapt to the environment of the excavation face and significantly improve the tunneling speed, which can alleviate the tension of the mine production connection.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

YL: conceptualization, supervision, and writing—original draft. DR: methodology, writing—review and editing, and data curation. CZ: validation, resources, investigation, and formal analysis. ZD and HQ: validation and formal analysis. CL: review and editing. All authors contributed to the article and approved the submitted version.

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Conflict of interest

Author YL was employed by the company Shandong Energy Group Xibei Mining Co., Ltd. Authors DR and CZ were employed by the company Shaanxi Zhengtong Coal Industry Co., Ltd.

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