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Adaptive Modification of TBM Tunneling in Coal Mine Roadway and Disaster Control Technology for Complex Geological Conditions

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Abstract: Many mines have introduced the tunnel boring machine (TBM) to improve the efficiency of rock tunneling because of its high propulsion capacity, safe working space, and intelligent equipment. In contrast, the operating environment of coal mines is often under complex geological conditions such as high ground stress, large depth of burial, high temperature, water damage, and large construction angles, making it difficult to apply traditional TBMs in coal mines. Taking the TBM of Gaojiapu Coal Mine of Zhengtong Coal Industry as an example, this paper introduces the coal mine adaptability transformation and construction technology optimization of the equipment, optimizes the design of the roadheader department of the equipment, increases the support operation space and reduces the empty roof distance, shortens the length of the whole machine and transforms the walking structure to enhance its maneuverability and convenience, and applies the monorail crane to the auxiliary transportation system of TBM. This paper proposes the theory of TBM tunneling disaster control in complex geology, research and discussion on TBM jamming, impact pressure, cooling prevention and control, and water damage in complex geological conditions. The results obtained were applied at the Zhengtong Coal Industry in engineering practice, resulting in an average monthly progress of more than 200 m, which is more than three times more efficient than full rock heaving, and also reduces the work intensity of tunneling personnel and promotes the development of coal mining. The final part of the article looks at the future application of TBMs in coal mining.

Keywords: open TBM; roadway excavation; complex geological conditions; TBM applications

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1. Introduction

Coal resources are abundant and will remain the main energy source in China for a long time in the future. The healthy development of the coal industry is of great significance to China's economic development and energy security [1–3]. However, the traditional roadway technology in coal mines is still dominated by general and artillery tunneling, which faces problems such as low efficiency, poor working environments, and multiple repairs of the tunnel. Full-section tunnel boring machines are used for roadway tunneling in coal mines for their high efficiency of tunneling, intelligence of equipment, and few operators [4]. At present, due to the difference between the actual operating environment of coal mines and that of traditional TBMs [5], TBMs are in the early stage of exploration in the tunneling of domestic coal mines and preliminary application practices have been achieved in the mines of Huainan Mining, Shandong Energy, and National Energy [6].

TBMs were first introduced to coal mine roadway boring applications in 1999 at Wangjialing coal mine [7]. In recent years, the DZ028 hard rock roadheader manufactured by China Railway Construction Heavy Industry Group was used for the first time to dig 5800 m in 2014 in the Xinjiang Flooded Bay coal mine subleveling project, which took 1160 calendar days and reached a maximum daily advance of 18 m. In 2015, a hand-jaw roadheader was developed by China North Heavy Industry Group Co. It was the first production line of TBM boring, with an optimal daily advance rate of 30.7 m and an average daily advance rate of 13.5 m. In 2016, Shenhua Shendong Tenglianta Coal Mine (China) started construction of its No. 2 auxiliary shaft with a TBM that is capable of crossing hard, soft, and mixed ground. The project produced the best monthly advance rate of 639 m, with an average monthly advance rate of 500 m for four consecutive months. In the last decade, the use of TBMs in coal mines has gradually grown, with more than 10 TBMs already in use in coal production after 19 years. Figure 1 shows the statistics of the number of TBMs used in coal mines in recent years [8].

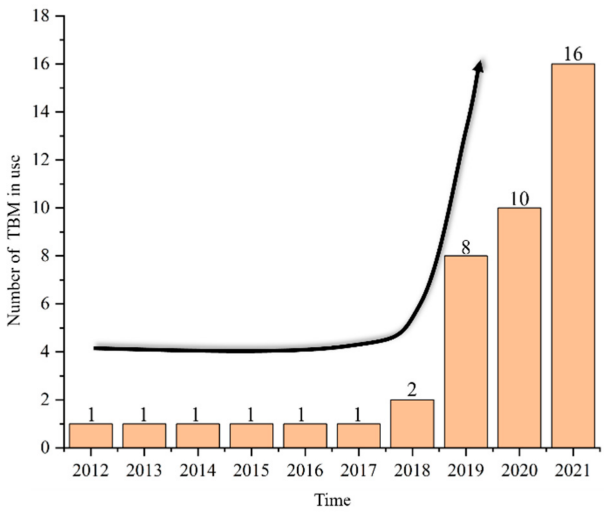


Figure 1. Number of TBMs in use.

However, in the field of coal mining, the mining depths of major mines in the central and eastern parts of China have reached 800–1000 m, with 47 mines mining deeper than 1000 m; the maximum mining depth of Suncun coal mine in Shandong exceeds 1500 m [9]. This is due to the complex stress environment of "three highs and one disturbance" [10], which causes the application of TBMs to face a series of challenges, such as large size TBM transfer and integration and high levels of stress in the deep part of the mine. The application of TBMs will face a series of challenges, such as large-size TBM transfer and integration, stability control of the surrounding rock of the installation chamber under the high level of deep stresses, rock breaking mechanism of the hobbing [11], stability control of the surrounding rock, and long-distance continuous transportation of the large cross-sectional roadway in one pass, cooling and dust removal of the tunneling machine, advance geological prediction and forecasting [12], and impact pressure prevention and control [13].

The Zhengtong Coal Industry, a 1000-m deep shaft in central and western China, faces a complex stress environment of "three highs and one disturbance" and multiple geological hazards such as impact ground pressure, high temperature, high stress, etc., and may face equipment jam, impact ground pressure, sudden surge water, and geothermal hazards during TBM boring [14]. Therefore, this paper explores the adaptation and application of TBMs in complex geological conditions based on TBM application in the Zhengtong Coal Industry, which is important for the construction of intelligent mines in western mines, alleviating mining conflicts and improving the stability of the mines. Therefore, this paper explores the adaptation and application of TBMs in complex geological conditions based on the practice of TBM application in the Zhengtong Coal Industry, which is of positive significance for the construction of intelligent mines in western mines, alleviating mining conflicts and promoting safe and efficient production.

2. Overview of TBM Application Project in Zhengtong Coal Industry

2.1. Project Background

The Zhengtong Coal Industry is mainly mining the Yan'an Group 4 coal seam, buried at a depth of 1000–1100 m. The coal seam histogram and geographical location of the mine are shown in Figure 2. The mine is a high gas mine, and the coal seam is a spontaneous combustion coal seam; and, the coal dust is at high risk of explosion. The mine's geological conditions are also complex, with deep water, high ground pressure, high temperature, high gas, high pressurized water, soft rock, and other natural disasters.

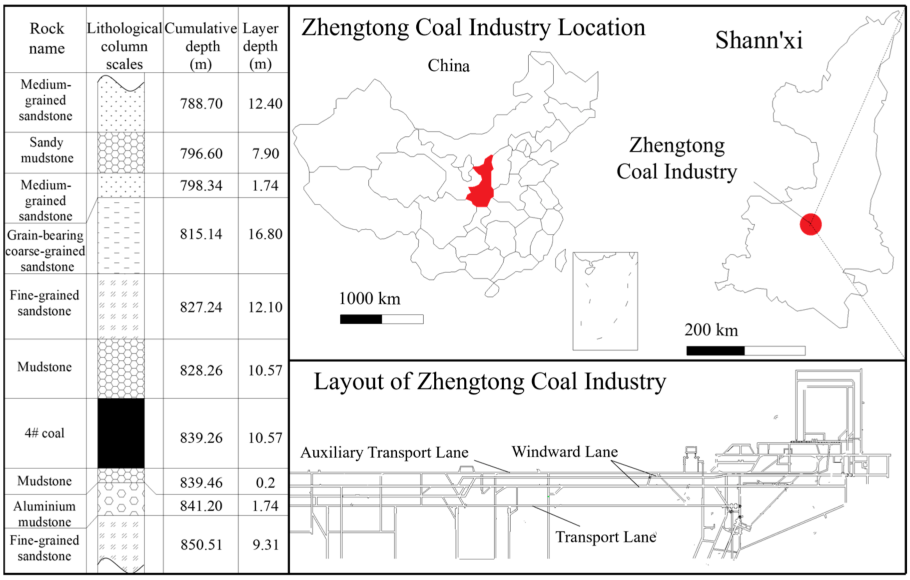


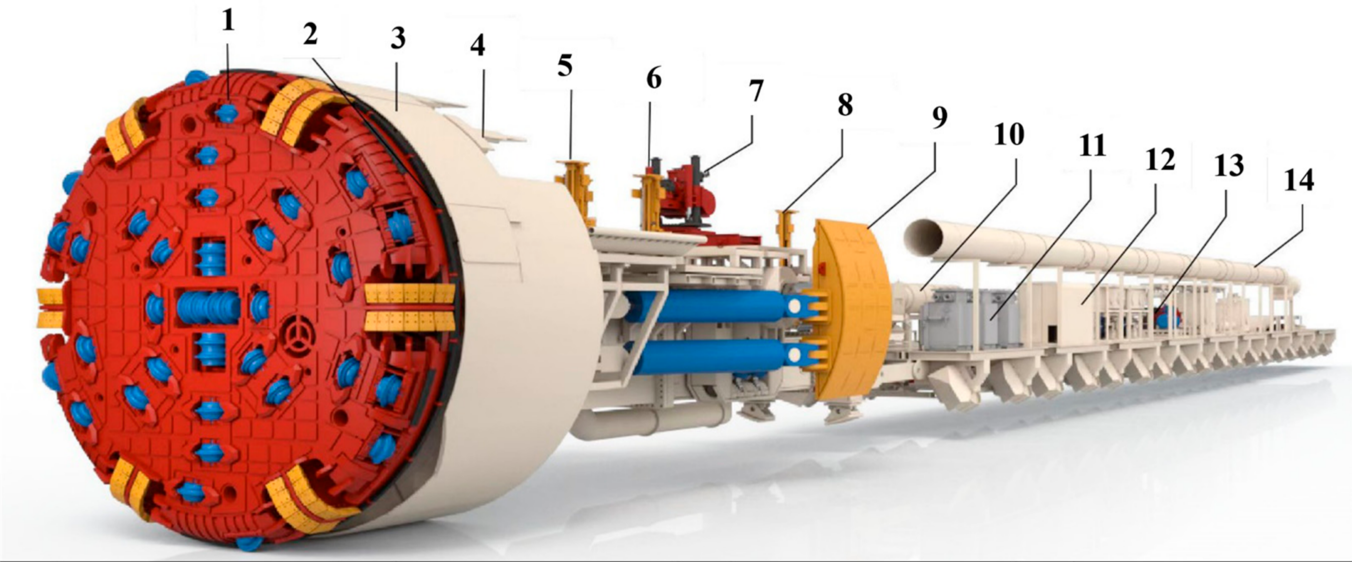
Figure 2. Background map of Zhengtong Coal Industry project.

The plan of mine excavation engineering is shown in Figure 2. In order to reduce the impact of ground pressure, the four openings in the west area are all laid out in the rock layer, which is a huge amount of exploration work and seriously restricts the production continuity of the mine. Take the west auxiliary transportation road as an example—the total design length is 6500 m, in view of the existing mine production succession. If the ordinary "integrated excavation + gun digging" construction system is adopted, the Zhengtong Coal Industry will have a one-sided production for up to one year when the four or five mineing area workings are successive, and by then the mine will reduce production by about 1.5 million tons, which will seriously reduce the economic efficiency of the mine. The economic efficiency of the mine and the labor intensity of the workers will be increased. Therefore, in order to achieve normal production of the mine, it is necessary to introduce advanced rock tunneling technology and carry out research on the adaptation of TBMs in complex geological conditions and disaster control theory.

2.2. Main Systems of the Third TBM in Zhengtong Coal Industry

The full-section hard rock boring machine mainly consists of the main machine and the connecting bridge rear support; the model chosen for use in the Zhengtong Coal Industry is an open TBM, and the main part of this model TBM consists of the cutter, shield, inner and outer kai (or inner frame, horizontal support), main drive, front and rear support (headstock, rear support), etc.

Through the exploration of the first two TBMs in field practice, the main system diagram of the third full-face hard rock roadheader used in Zhengtong Coal Industry is shown in Figure 3.



1	Cutter	2	Drive Systems	3	Shields	4	Finger Shield
5	Anchor Drilling Rig System For Zone L1	6	Anchor Drilling Rig System For Zone L2	7	Overrunning Rig Systems	8	Anchor Drilling Rig System For Zone L3
9	Auxiliary Support Boots	10	Dust Removal Systems	11	Power Distribution Systems	12	Control Systems
13	Hydraulic Fluid Systems	14	Ventilation Systems				

Figure 3. TBM composition and system.

3. Adaptation of TBM I and Intelligent Processes in Complex Geological Conditions

As TBM tunneling technology has been used in transportation, water conservancy, and railway and municipal fields in the past, it is less used in mining engineering, and the existing mature TBM full-section tunneling machine can hardly meet the actual needs of coal mines. This will make it more suitable for the special application environment of coal mines, promote the popularity of TBMs in the field of mining engineering, and improve the efficiency of roadway boring in coal mines.

3.1. Full-Section Roadheader Coal-Mining Structural Parameters Transformation and Process Upgrade Optimization

Unlike the previous environment of TBM use, the environment of a coal mine excavation often has the characteristics of a large depth of burial, high ground stress, a sudden surge of water, and narrow operating space, whereas for the original TBM in complex geological coal mine excavation conditions, the support operating space is poor and the distance between the empty roof is large. There cannot be timely support, so workers and machines face the risk of roofing during excavation operations, seriously threatening the safety of personnel and equipment. At the same time, the support work space is insufficient, and the support speed often cannot keep up with the digging speed, which affects the digging efficiency. For this reason, the Zhengtong Coal Industry has designed a coal mine adaptation of the original TBM tunneling machine.

(1) Modification of roadheading machine department:

There are two types of TBMs: open type and shield type. Open TBMs are mainly suitable for strata where the surrounding rock is relatively intact and self-stabilizing. Its supporting means generally adopt the commonly used anchor spray form in coal mine roadway, with shorter shields and relatively flexible operation, and easy turning. The shield is longer and less flexible. In order to effectively avoid the large deformation of high-stress soft rocks during TBM tunneling or uneven shield forces during construction of the roadway through layers, and considering the small cross-section of the deep vertical coal mine roadway and the difficulties in turning the roadway transportation, it is necessary to design small turning radius TBM equipment. Therefore, it is reasonable to use an open TBM, which is more flexible in the adjustment of support(Figure 4), so the original main structure is improved to adapt to safe and efficient TBM tunneling construction under different rock formations, and the original main beam is installed upside down to increase the space above the main beam. In addition, the hydraulic anchor drill rigs with different functions were installed to compensate for the travel of the support rigs and additional hydraulic cylinders were installed to automatically compensate for the slippage of the limits so as to realize the parallel and flexible construction of support while digging; the drill holes were automatically positioned through the swing limits of the drill rigs to improve the support efficiency, and the hydraulic finger shields were added above the overrunning anchor rigs to significantly shorten the working distance of the TBM while digging. This will significantly shorten the distance of air-top operation, protect the safety of personnel and equipment, and improve the working environment of workers when they are supporting.

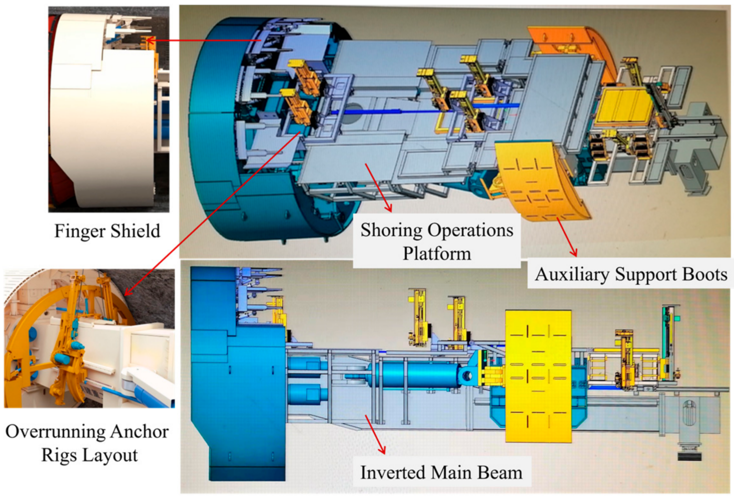


Figure 4. Segmented zoning large support work platform.

(2) Enhance the convenience and flexibility of the entire TBM machine:

By connecting the cutter plate directly to the reloading belt, the original host belt is omitted and a series of main drive systems such as the main motor, external shield, and other auxiliary structural components are designed to be located around the main beam so that the original four sections of the main beam are shortened to two sections of the main beam (Figure 5), which significantly shortens the length of the host and eliminates the touch bottom skid, connecting bridge and mixed spray system in the post-support system. The structure and equipment in the post-support system, such as the bottoming sheave, connecting bridge, mixed spray system, etc., which are not suitable for mine tunneling, have been eliminated. This modification allows the length of the first TBM used in the original Zhengtong Coal Industry to be reduced from 167 m to 75 m for the third TBM and the turning radius to be shortened from 500 m to 90 m, which improves the flexibility of the equipment and enhances the adaptability of tunneling in the complex tunnel system of the mine; shortens the construction time and installation time of the assembly and installation chambers, reducing the preparation period for tunneling; shortens the empty roof distance, ensuring the on-site support and improving the space of the equipment. This shortens the construction time and installation time, reduces the preparation time, and shortens the distance to the top of the roof, ensures the safety of the construction, and ensures efficient and continuous TBM tunneling.

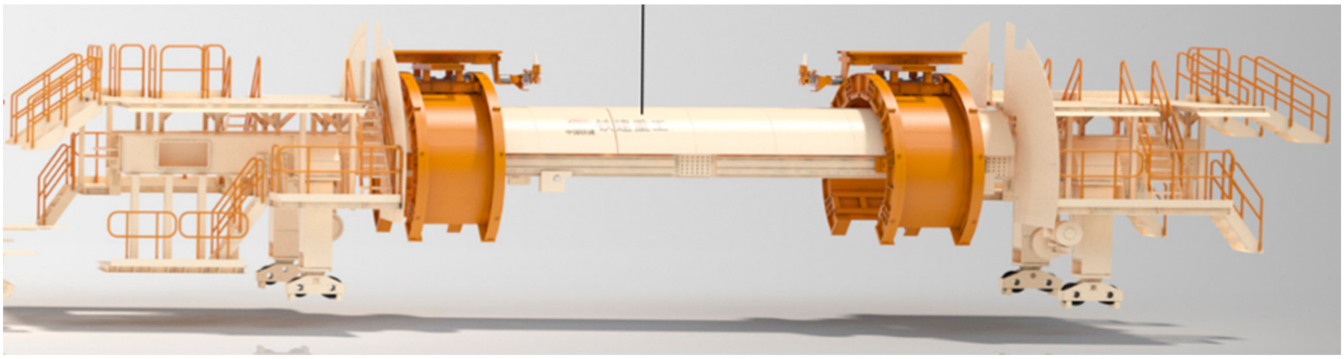


Figure 5. Modified walking structure.

(3) Modification of auxiliary transportation system:

By optimizing the arrangement of equipment such as electrical switches and hydraulic pump stations attached to the TBM, the electrical equipment, cables, hydraulic control system, and hydraulic piping are arranged on both sides of the trailer, whereas the belt conveyor is arranged at the bottom of the trailer to realize the electro-hydraulic separation of the internal space arrangement of the TBM, ensuring the space for the monorail crane to run in the middle and upper part of the tunnel, and the anchor arrangement of the roof plate through the third trailer of the TBM to realize the installation of the monorail crane. The installation of monorail crane can realize one-stop material transportation to excavation face. Furthermore, it will change the laying track to rubber wheel type structure, increase the slag dialing mechanism, cancel the track laying procedure(Figure 6), and further reduce the dragging resistance. It will ensure efficient and continuous TBM boring, ensure site support, and improve construction safety. The improvement of the trailer travel structure and the application of the monorail crane have greatly enhanced the flexibility of the TBM, which is better suited to the digging environment of coal mines in complex geological conditions.

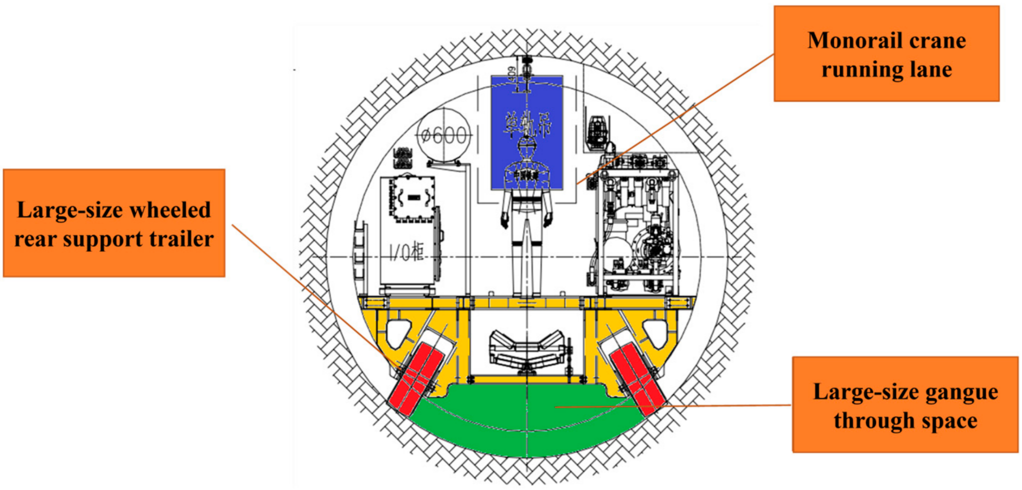


Figure 6. Monorail crane arrangement.

A table comparing the structure and function of the TBM before and after its modification is shown in Table 1:

Table 1. Table comparing structure and function before and after TBM renovation.

Structure or Function	Converted TBM	Original Open-Type TBM
Main beam construction	Inverted main beam for increased upper space	Small working space above the original main beam
Shoring work platforms	Large working space and multi-stage support	Small working space does not allow for more anchor drilling rigs
Excavation of empty roof distance	Finger-shaped shields with small headroom for greater safety	Dangerous support work due to large empty roof distance
Achieving electro-hydraulic separation	Yes	No
Overall length	75 m	167 m
Turning radius	90 m	500 m
Walking structure	Rubber-wheeled travel structure	Rail skids, need to lay track in advance
Auxiliary transport systems	Monorail crane, one stop for materials straight to the working surface	Rail transport, manual transfer required

3.2. Intelligent Construction and Tunneling Techniques for TBMs in Deep and Complex Geological Conditions

TBM tunneling is the most important part of TBM construction. TBM tunneling is a system operation that affects the whole body, and a series of work such as slagging, anchoring, steel arch support, anchor spraying, material transportation, water supply and drainage, slag unloading, etc. must be completed at the same time as changing steps and tunneling. Different parameters of excavation must be selected according to different surrounding rock conditions.

The TBM construction process uses "continuous digging and support parallel" operation, i.e., the TBM cutting rock advances a support row distance and then carries out timely support to control the surrounding rock to ensure the safety of the construction space. The TBM cuts the rock at the same time as it supports, clears slag, and extends wind, water, and electricity. With the change in step and digging at the same time to complete a series of work such as gangue discharge, support, material transportation, water supply, and drainage.

The intelligent TBM tunneling process is shown in Figure 7. In complex geological conditions, advanced geological forecasting technology is needed to accurately forecast the adverse geology in front of the cutter and to initiate construction plans for different geological conditions in order to give full play to the performance advantages of TBM equipment and to ensure the safety of personnel and equipment. The first step is to conduct the overall geological exploration before the construction so as to master the geological conditions such as stratigraphic lithology, geological structure, and hydrogeology in the area. The second step is to judge the possible geological risks by observing the geological environment in front of the tunnel excavation, and then to divide the geological anomaly area according to the physical exploration data. Finally, according to the changes in the tunneling parameters during the construction of TBMs, we analyze and judge the risk of jamming and activate the response plan under different geological risks.

Finally, based on the advanced geological forecast data and the characteristics of the TBM boring process, the construction plan of the boring process is formulated, and the main processes of rock breaking, continuous slagging, rapid support, ventilation and dust removal, water supply, and drainage, etc., are carried out in a coordinated manner, forming a technical system of the TBM boring process for vertical shaft development coal mines under complex geological conditions.

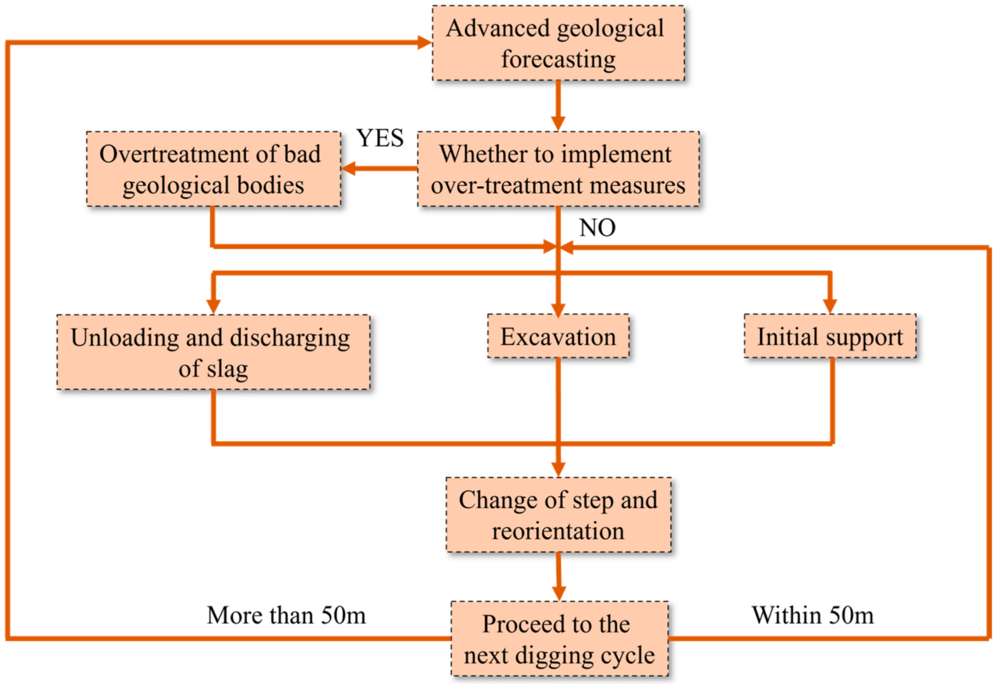


Figure 7. TBM intelligent tunneling process.

4. Research on Disaster Control Theory and Technology for TBM Tunneling in Complex Geological Conditions

TBM crossing weak coal strata (fracture zone, geological structure, etc.) is a highly concerning and urgent problem in the industry. In long-distance advancement, problems such as inward trapping of the braced boot lane gang and jamming of the machine will inevitably occur, which seriously restrict the progress of the excavation [15]. At the Shaanxi Zhengtong Coal Industry, multiple disasters are complex, limited by geological factors such as mining depth and traversing soft strata in the coal system, the TBM boring process of the west pioneer lane is faced with complex geological conditions, which seriously restrict the safe and efficient intelligent tunneling of the mine rock lane. In this section, based on the geological conditions of production in the west auxiliary transportation lane coal mine, we propose the TBM development tunneling program from the consideration of safety, construction technology, transportation method, construction efficiency, and economy, and make an in-depth analysis with the disaster problems faced during TBM tunneling such as jamming disaster through a coal seam, impact ground pressure, sudden water surge of the TBM in long distances uphill, and heat damage of cooling and dust removal to form complex geological conditions. In addition, we will analyze the disaster mechanism and prevention and control technology of TBM tunneling under complex geological conditions.

4.1. Mechanism and Prevention and Control of Jamming in Large Burial Depth Crushing Zone

The TBM tunnel excavation space profile is shown in Figure 8. When the TBM is working, the shield and the cutterhead are connected, and the over-excavation disc cutter has a certain amount of over-excavation on the tunnel face, which reserves a certain space and time for the unloading deformation of the tunnel surrounding rock.When the deformation of the surrounding rock around the shield exceeds the amount of deformation reserved for excavation, the surrounding rock starts to make contact with and squeeze the shield, which in turn generates frictional resistance to it. When the thrust of the TBM cannot overcome the frictional resistance R_f generated by the surrounding rock on the shield, the shield of the TBM is stuck. In the process of contact between the deformation of the surrounding rock and the shield, when the contact frictional resistance is greater than the TBM thrust, a jam occurs [16]. Therefore, two conditions must be met for a TBM shield to jam: (i) the surrounding rock deformation exceeds the excavation gap; (ii) the contact friction resistance is greater than the TBM thrust.

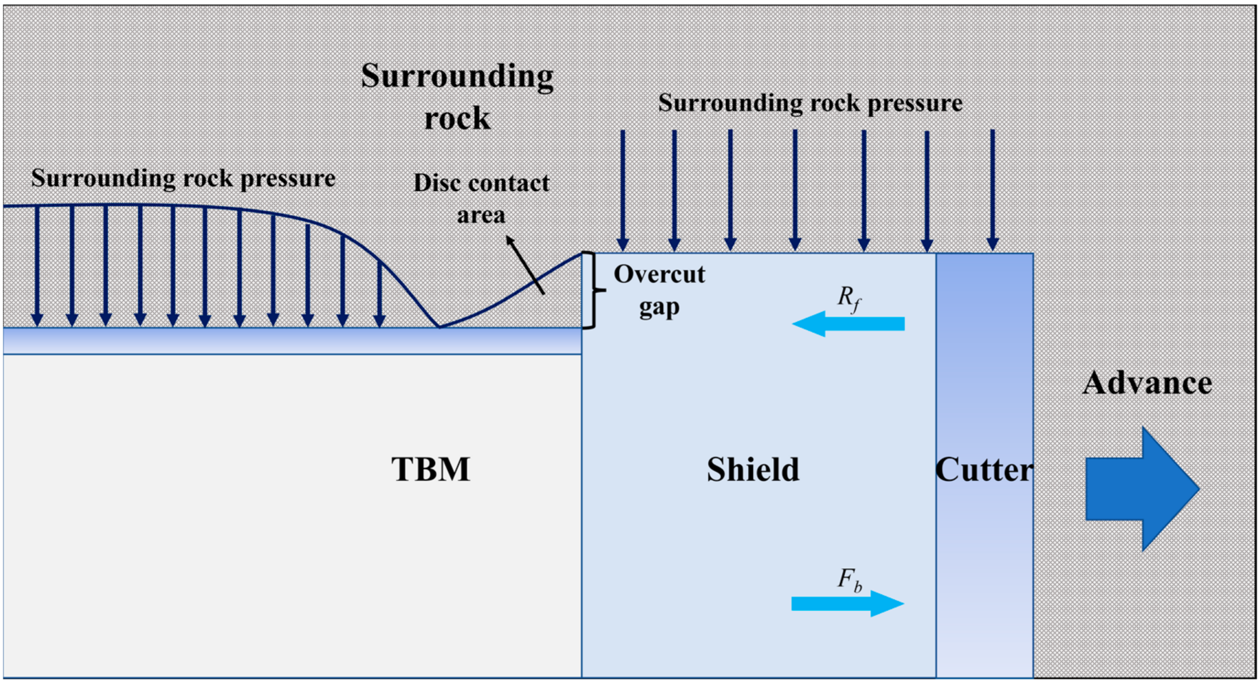


Figure 8. Deep buried roadway TBM roadway excavation space profile.

In deep complex geological conditions, TBM tunneling equipment jamming is still mainly based on shield and cutter jamming [17]. During the construction of the TBM through the coal seam in the Shaanxi Zhengtong Coal Industry, it also faces certain impact ground pressure jamming disasters, etc. Therefore, based on the engineering geological conditions of the site, we propose technical measures for prevention and control of the TBM through coal seam jamming in the Zhengtong Coal Industry.

(1) Adjustment of technical parameters of TBM tunneling equipment

The mine excavation workforce adopts a TBM open-type hard rock boring machine. This type of TBM shield is shorter and the surrounding rock can be supported in time after the adaptive transformation of TBM coal mine. During the excavation, the geological conditions of the surrounding rocks and its changes can be grasped in real time, and it can be used to adjust the excavation parameters according to the geological conditions. For example, setting a reasonable expansion gap, reducing downtime when crossing weak strata such as coal seams, and choosing a higher digging rate to reduce the empty roof distance and empty roof time.

(2) TBM digging attitude adjustment

The guidance system automatically detects the TBM attitude every few seconds. The TBM operator adjusts the thrust value of each propulsion cylinder of the TBM to correct the attitude of the main machine according to the relevant data, and the TBM can make adjustments to the digging direction at any time during the digging process or at the end of the digging stroke. The laser guidance device on the TBM is first used to determine the deviation of the current position of the tunneling up and down, left and right, and circumferentially and determine the current position condition of the TBM. In order to calibrate the accuracy of the automatic measuring system and move the movable bracket to set up the rear view reference point, the surveyor calibrates the accuracy of the automatic measuring system to ensure the accuracy of the attitude.

4.2. Impact Pressure Prevention and Control Technology for TBM Tunneling in Deep Well and Large Section Rock Tunnel

The excavation of coal mine tunnels is often accompanied by structural damage to the surrounding rock mass [18,19]. There are thick hard rock layers in the roof of the coal seam mined in the Zhengtong Coal Industry, and the roof of these thick hard rock layers has better energy storage conditions (hard, dense, good integrity, thick rock layer, large overhanging roof distance, etc.). In addition, the depth of coal seam tunnel endowment is between 800–1000 m, the burial depth is large, and a large number of mining hollow areas are distributed around the tunnel, resulting in a large amount of elastic energy accumulated in the stress concentration area of the tunnel surrounding rock. In the hard roof breakage, fault activation and other dynamic stress-induced stress concentration areas easily cause dynamic instability. The current main measure for impact ground pressure protection in the coal seam tunnel is to strengthen the support, and dynamic damage can also occur in the coal seam tunnel under high-strength support [20].

Combined with the geological conditions of the mine, the research on the prevention and control of impact ground pressure during TBM tunneling in the environment of large burial depth and thick hard roof, and the prevention and control technology of impact ground pressure in coal seam roadway is proposed: during the TBM tunneling process, the possible deep impact ground pressure is predicted quantitatively by real-time observation of the deformation of the roadway surrounding rock. In order to increase the damage range and bearing structure radius of the roadway and improve the strength of the rock surrounding the roadway, based on the failure criterion of impact ground pressure prevention and control, we proposed the method of combining drilling and blasting with surrounding rock grouting in the stress concentration area to prevent and control the impact ground pressure disaster in the coal seam tunnel [21,22], and the schematic diagram of the joint protection measures is shown in Figure 9. Finally, pressure relief boreholes are constructed to relieve pressure in high-level stress sections or faulted tectonic sections by means of control techniques such as over-advanced pre-grouting ground improvement and local lining of the TBM shield deformation.

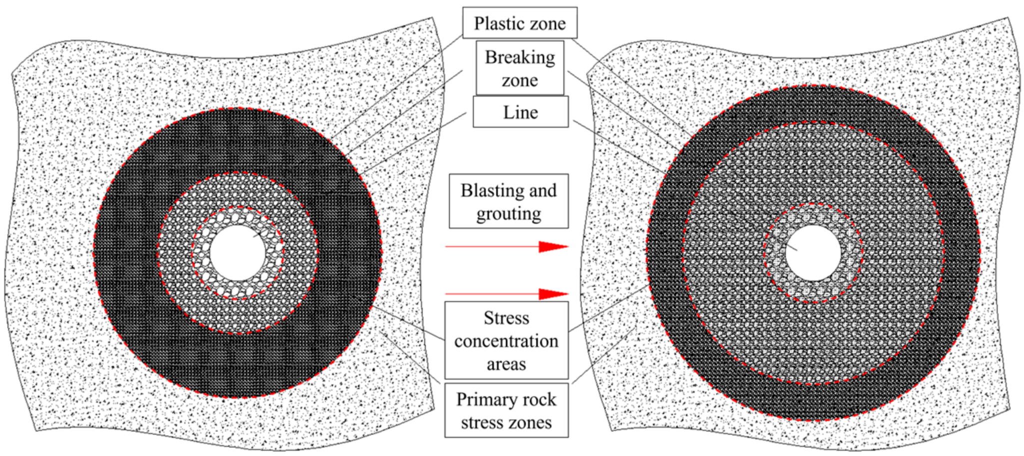


Figure 9. Schematic diagram of joint protection measures for impact ground pressure.

4.3. Deep High-Temperature Mine TBM Tunneling Temperature Reduction and Prevention and Control Technology

Unlike the previous TBM use environment, as China's coal mining gradually shifts to the deeper part, deep shaft coal mines will face high geothermal geological hazards, which will present new challenges and problems for TBM use [23]. To study the sources of thermal hazards in deep shaft coal mines, the author investigated the main influencing factors of thermal hazards in large buried deep coal mines in China, and the findings showed that the main heat sources affecting the generation of thermal hazards underground are heat dissipation from surrounding rocks, heat dissipation from hot water, heat dissipation from electromechanical equipment, compression heat, and oxidation heat. As a typical high geothermal mine, when the Zhengtong Coal Industry uses TBMs to dig the auxiliary transport roadway in the west area, the heat dissipation from the surrounding rock and TBM digging equipment is also beneficial because the roadway is a full rock roadway and the digging site is at the end of ventilation, which exacerbates the heat damage in the mine, and heat damage is an important risk factor for safe and efficient TBM digging in deep high-temperature mines [22]. Effective means of heat damage control work must be taken quickly during TBM boring construction, and cooling techniques for deep mines are adopted to:

① Use the existing cooling system; install an RWK1350 air cooler in the track chute of the coal mine face to cool down the working face. ② The air cooler is directly strung into the air cylinder of the local ventilation fan to cool the air pressed into the working face to achieve the purpose of cooling down. ③ Install the MK-300 air cooler in the trailer of TBM equipment so that it can cool down the middle of the whole machine and ensure that the air pressed into the working face does not increase in temperature. ④ The design adopts the press-in ventilation method commonly used for TBM construction roadway ventilation. The air volume required for the auxiliary transportation roadway in the west area should be distributed according to the heat dissipation requirements of the large boring equipment to ensure that the temperature of the boring working face does not exceed 26 °C.

4.4. TBM Tunneling Water Damage Control Technology

The hydrogeological type of the Zhengtong Coal Industry is "extremely complex" and the mining activities are threatened by continuous large water surges in the overlying Luohe Formation aquifer [24,25]. The water conduction by fault fissures during TBM boring is the main risk of surging water during long-distance and near-horizontal uphill TBM boring. Scientific advance geological prediction is the main technical measure to prevent and control the risk of water inrush in tunneling.. Considering the technical problems of mine roof water damage prevention and control, we choose to adopt the long-distance uphill boring program; The roadway is easier to be drained due to tunneling along the uphill.. The roadway can achieve the self-flow drainage of rainwater in the TBM boring roadway and construction water on the front slope, so the TBM boring project mainly faces the dangers of water drenching the roof of the boring face and water conduction from fault fissures. In this regard, the following key technologies are proposed for TBM tunneling in the face of fracture zones and high gushing water strata:

(1) The coal mine TBM tunneling process involves the complex engineering of a series of geological and hydrogeological problems: the construction process often encounters fissure aquifers, fault fracture zones, fracture development of the surrounding rock, and other complex strata, causing water accumulation. TBM support boots lack support for the surrounding rock, have difficulty advancing, and other problems. The construction through the fault fracture zone is prone to large deformation, collapse, and other disasters, seriously affecting the construction safety and progress, and endangering the safety of personnel [26]. Therefore, through the control technology of advanced pre-grouting stratigraphic improvement and local lining of TBM shield body deformation, the problem of shield jamming under soft rock geological conditions is solved; pressure relief boreholes are constructed for pressure relief in high-stress sections to solve the problem of shield jamming under high ground stress conditions; the cutter structure of TBM equipment, support matching method, and TBM backing function are optimized to create space conditions for the geological improvement of the working face and realize special stratigraphic pre-treatment.

(2) Adverse geological conditions forecasting and treatment to avoid water conduction by fault fissures during excavation In other words, it is divided into two parts, namely, over-prediction and comprehensive management. In terms of advance forecast, it is mainly conducted through the macro forecast of bad geology, long-term and short-term advance

geological forecast of the bad geological body of the cave, advance drilling, and proximity warning of construction geological hazards. In the aspect of comprehensive management, it is mainly based on the above forecasting and the implementation of different treatment plans and treatment measures for the nature and types of adverse geological bodies and possible construction geological hazards.

5. Overview of TBM Application in the Zhengtong Coal Industry

After the application of the TBM tunneling equipment intelligent tunneling system, the project completed the development of the auxiliary transport lane in the west area of the Zhengtong Coal Industry as scheduled. As shown in Figure 10, during the practical application of the test tunneling period from January to August 2021, the average monthly progress using TBM construction reached 272.9 m, the maximum monthly advance was up to 305 m, and the daily progress could reach more than 10 m. The construction efficiency was twice as high as that of the comprehensive tunneling of the rock lane and seven times as high as that of the general tunneling of the rock lane (all rock tunneling in the mine was done by TBM in February), making the tunneling efficiency of the lane greatly improved. It can effectively alleviate the problem of succession tension in the Zhengtong Coal Industry. After that, the mine continued to promote the application of TBM equipment to the smooth introduction of lightweight TBM tunneling equipment for 403 surface drainage tunneling; the current application of the footage effect is remarkable, promoting the improvement of the economic and technical benefits of the Zhengtong Coal Industry, and provided a new idea for mines with similar conditions to solve the problem of mining succession. Furthermore, its successful practical experience provides a sufficient reference basis for changing the current mine construction concept, giving full play to the advantages of TBMs, guaranteeing mine mining succession, and driving the transformation and upgrading of the traditional mining industry.

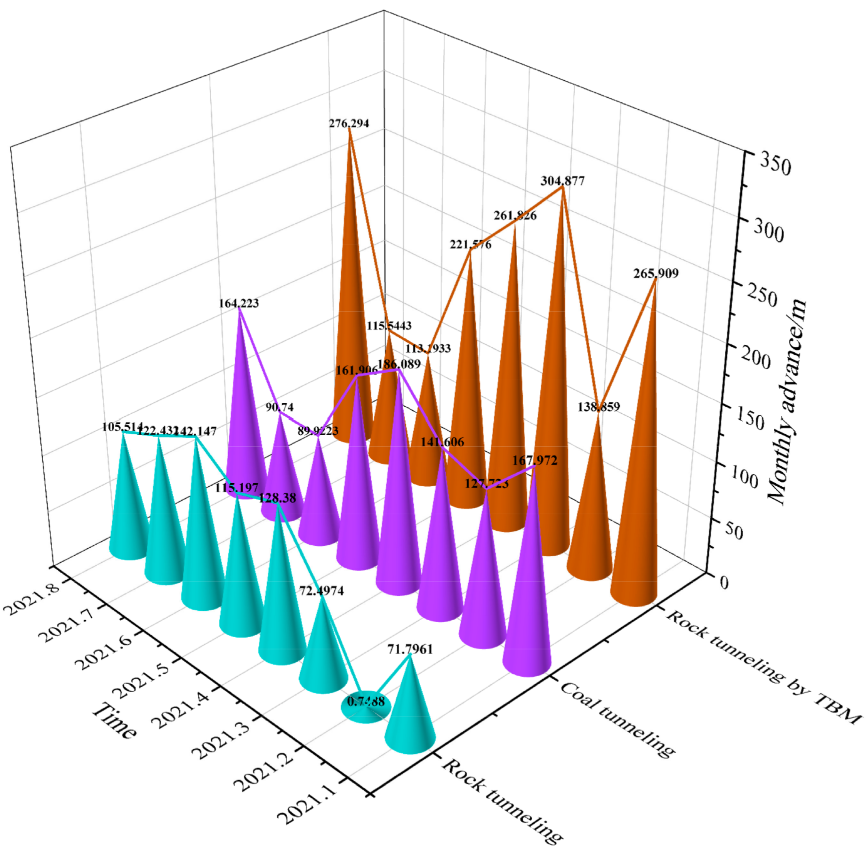


Figure 10. Comparison of the effect of ZTT6530-TBM boring footage.

A site plan of the downhole TBM is shown in Figure 11. The Zhengtong Coal Industry has adopted and designed TBMs to adapt to the geological conditions of the coal mine and to the integration of various systems and processes so that the tunneling efficiency of the roadway is greatly improved, which can effectively alleviate the problem of succession tension in the Zhengtong Coal Industry. As the use of TBMs for coal mine rock tunnel construction is still in the primary development stage, the successful introduction and application of TBM equipment, its technical experience in structure optimization, and improving the adaptability of working conditions is worth learning from and is a further deepening of the promotion of mine-less personalized and intelligent operations, equipment, and working conditions. With the optimization of TBM equipment structure, shorter assembly and transfer period, more reasonable roadway planning, and lower cost of extended meters, mining TBMs will have a broader market prospect in coal mine rock tunnel construction from the comprehensive consideration of construction period, cost, and safety.

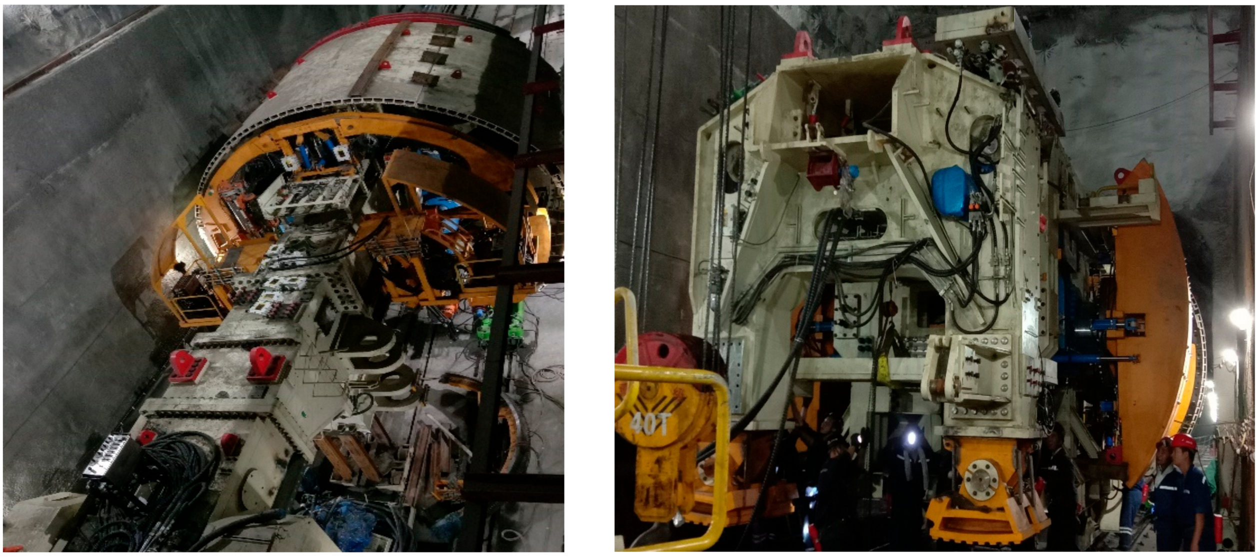


Figure 11. Site plan of underground TBM in Zhengtong Coal Industry.

6. Prospects of TBMs in Coal Mine Sector

Although TBMs are widely used and technically mature around the world, their application in coal mines is in the exploration and development period. For new equipment use environments, in-depth coal-mining TBM adaptation studies should also be conducted. The practical experience of the Zhengtong Coal Industry TBM application provides some reference for the direction of coal mining TBM adaptation:

(1) Enhance the mobility and convenience of TBM in complex geological conditions

Unlike the general use of TBMs, the installation of a TBM underground requires the preparation of the assembly chamber, which increases the cost and preparation time for mine production and requires frequent adjustment of the machine's attitude and boring direction due to complex geological conditions. Shortening the length of the machine, optimizing the structure of the machine, quick and efficient transfers, and modularizing and integrating large components can all enhance the mobility and convenience of the TBM. Enhancing geological prediction during tunneling, e.g., using acoustic emission [27], infrared detection, and other means to build transparent geological models can also enhance the mobility of TBMs in complex geological conditions.

(2) Integrated application of TBM and coal mine support process

As the mining depth increases, the complex geological conditions faced by coal mine excavation gradually deteriorate, which poses new problems for support during excavation [28]. The high level of ground stress in mines with deep and complex addresses and the low strength of the surrounding rocks will produce continuous and high-intensity deformation in the weak or fractured zone under strong ground stress, which not only makes the support more difficult but also destroys the already constructed support measures by the continuous deformation of the surrounding rocks [29]. Failure to control the surrounding rock during the TBM boring process can lead to the risk of the TBM jamming. For this reason, it is important to strengthen the support during the TBM boring process and shorten the distance between the empty roof. Timely adjustment of the support scheme with the help of advanced geological forecasting, and the application of various support measures such as advance overrun support, overrun grouting, reinforcement row, steel arch, anchor net/rod/rope, shotcrete, and prefabricated pipe sheet in mining TBM construction enhance the adaptability of TBMs in complex geology [30].

(3) Intelligent and autonomous tunneling of TBMs

TBM tunneling is already fully automated, and with the adaptation of complex geology, the conditions for intelligent and unmanned tunneling are available. The research on intelligent TBM tunneling should follow the principle of "perception as the basis, information fusion as the center, and intelligent tunneling as the goal", and establish the overall research system of TBM intelligence (Figure 12), which includes: edge perception layer to improve the equipment's ability to detect and warn of adverse geological information in front of the roadway tunneling work. The data transmission layer aggregates different types of data, transmits them to the platform layer, and stores them in a classified manner to ensure the real-time integrity of each type of data for later data mining and analysis; (1) the platform fusion layer is used for deep mining and fusion of the acquired multi-source information for big data analysis, knowledge base, and rule base; (2) the decision application layer is used for the establishment of the TBM intelligent system (Figure 11); (3) the platform fusion layer is used to deeply mine and fuse the acquired multi-source information for big data analysis, knowledge base and rule base establishment; (4) the decision application layer gives TBM intelligent assisted driving suggestions based on the developed expert knowledge base, virtual tunneling experiment platform, tunneling parameter estimation model, and intelligent guidance model [31].

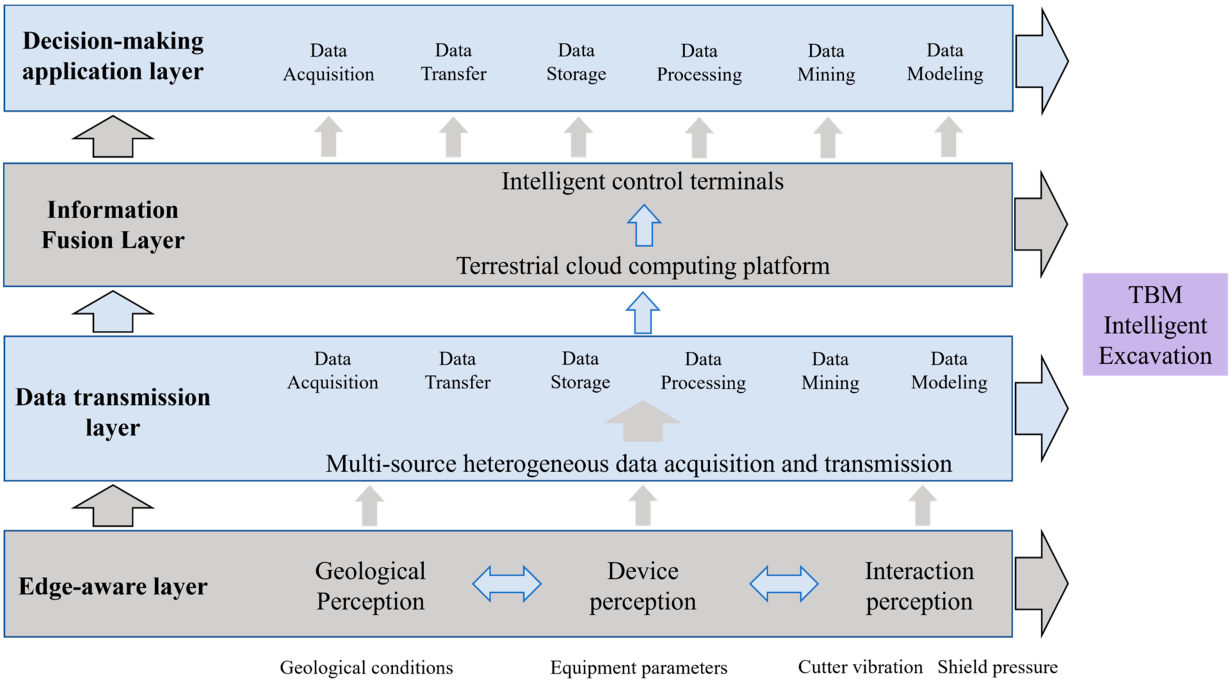


Figure 12. TBM intelligent overall research system.

7. Conclusions

This paper presents a sample study of TBM tunneling in a coal mine with complex geological conditions, presents the problems and solutions that may be encountered in tunneling under these conditions, and proposes a specific program for the adaptation of TBMs to coal mining, through which we can draw the following conclusions:

- In response to the characteristics of the TBM tunneling project in the Zhengtong Coal Industry, combined with the original open-type TBMs, the full-section tunneling machine is upgraded and optimized with the modification of coal mine structure parameters, the upgrade and optimization started with the modification of the roadheader section, the optimization of the overall machine length and travel structure, and the auxiliary transport system. This enhances the flexibility of the equipment, shortens the empty roof distance of the support, reduces the installation time of the equipment, and realizes the material transportation directly to the working face. The auxiliary transport system has been modified to enable direct material transport to the working face, making it more adaptable to the complex environment of deeper coal mines than conventional TBMs. The TBM construction optimization and intelligent tunneling process for deep and complex geological conditions are proposed, and the main processes of rock breaking, continuous slagging, rapid support, ventilation and dust removal, water supply, and drainage are realized, forming a complete set of intelligent coal mine TBM tunneling standards and specification system.
- Focusing on the applicability of a deep shaft TBM tunneling system in complex geological conditions, we propose to preassess the engineering geological conditions of the roadway, scientifically carry out advanced geological prediction, and improve the ability to cope with adverse geological conditions. Furthermore, study the mechanism of TBM tunneling in complex coal stratigraphic conditions, propose advanced geological drilling and soft strata slurry modification technology, and reduce the progress caused by lithological changes and sudden geological disasters. The study also proposes a reasonable support scheme for TBM tunneling in terms of zoning, segmentation, and stratification, and finally establishes a key technology system for prevention and control of typical disasters in TBM tunneling under the coupling of multiple disaster-causing factors in deep wells to ensure the stability of TBM tunneling conditions.
- After the introduction of TBMs and their adaptation to coal mining, the Zhengtong Coal Industry has formed a highly efficient rock tunneling system with TBMs as the main part of the tunneling system, supplemented by comprehensive excavators, which has greatly improved the efficiency of rock tunneling and ensured the mine's mining succession and disaster management. The successful application of TBMs in the Zhengtong Coal Industry shows that TBMs have great application prospects in the coal mine field. In the future, we will conduct research on enhancing the flexibility and convenience of TBMs, the comprehensive application of TBMs and coal mine support technology, and the intelligent and autonomous digging of TBMs. It can promote the development of intelligent and less manned coal mines, thus improving the level of coal mine safety production and accelerating the transformation and upgrading of the coal industry.

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References

1. Kang, H.; Wang, G.; Wang, S.; Liu, J.; Ren, S.; Chen, P.; Qin, R.; Pang, Y.; Qu, Y. High-Quality Development of China's Coal Industry. *Strateg. Study CAE* **2021**, *23*, 130–138. [CrossRef]
2. Wang, G.F.; Ren, S.H.; Pang, Y.H.; Qu, S.J.; Zhen, D.Z. Development achievements of China's coal industry during the 13th Five-Year Plan period and implementation path of "dual carbon" target. *Coal Sci. Technol.* **2021**, *49*, 1–8.
3. Xie, H.P.; Ren, S.H.; Xie, Y.C.; Jiao, X.M. Development opportunities of the coal industry towards the goal of carbon neutrality. *J. China Coal Soc.* **2021**, *46*, 2197–2211.
4. Huang, X.; Liu, Q.S.; Shi, K.; Liu, J. Application and prospect of hard rock TBM for deep road way construction in coal mines. *Tunn. Undergr. Space Technol.* **2018**, *73*, 105–126. [CrossRef]
5. Hao, J.S. Present status and outlook of key technology for mine roadway heading equipment. *Coal Sci. Technol.* **2014**, *42*, 69–74.
6. Dai, E.H.; Lu, Y.Q.; Qiu, H.D.; Yan S., H.; Yang, T. Study on application of TBM construction technology in coal mine in Yunan-Guizhou area. *Coal Sci. Technol.* **2022**, *5*, 10–18.
7. Yu, Y.L.; Du, F. Optimization of super-long flat tunnel form in Wangjialing Mine. *Coal Eng.* **1999**, *9*, 14–18.
8. He, F.; Lu, Y.Q.; Dai, N.H.; Tian, Y.Z.; Wu, F.; Pan, S.C.; Zhang, S.; Chen, Z. Application of TBM in coal mine adaptability type selection analysis and new technology development. *Coal Sci. Technol.* **2023**, 1–13. [CrossRef]
9. Yuan, L. Strategic thinking of simultaneousexploitation of coal and gas in deep mining. *J. China Coal Soc.* **2016**, *41*, 1–6.
10. He, M.C.; Xie, H.P.; Peng, S.P.; Jiang, Y.D. Study on rock mechanics in deep mining engineering. *Chin. J. Rock Mech. Eng.* **2005**, *24*, 2803–2813.
11. Xia, Y.-M.; Lin, L.-K.; Wu, D.; Jia, L.-H.; Chen, Z.; Bian, Z.-K. Geological adaptability matching design of disc cutter using multicriteria decision making approaches. *J. Cent. South Univ.* **2018**, *25*, 843–854. [CrossRef]
12. Shang, Y.J.; Zeng, Q.L.; Zeng, Q.L.; Sun, Y.C.; Shi, Y.Y.; Yuan, G.X. Retrospective analysis of TBM accidents from its poor flexibility to complicatedgeological conditions. *Chin. J. Rock Mech. Eng.* **2007**, *26*, 2404–2411.
13. Zhang, H.W.; Hu, Z.F.; Fu, J.Y.; Chen, J.Y. TBM techniques for intelligent excavating large-section rock roadway in the deep high-temperature coal mines: Application of TBM in Xinkuang No. 1. *J. China Coal Soc.* **2021**, *46*, 2174–2185.
14. Liu, Q.S.; Huang, X.; Liu, J.P. Interaction and safety control between TBM and deep mixed ground. *J. China Coal Soc.* **2015**, *40*, 1213–1224.
15. Tang, B.; Cheng, H.; Tang, Y.; Yao, Z.; Rong, C.; Wang, X.; Xue, W.; Guo, S. Experiences of gripper TBM application in shaft coal mine: A case study in Zhangji coal mine, China. *Tunn. Undergr. Space Technol.* **2018**, *81*, 660–668. [CrossRef]
16. Wen, S.; Yang, S.Q.; Dong, Z.F.; Zhao, L.M. TBM jamming mechanism and control measures in deep buried tunnels. *Chin. J. Geotech. Eng.* **2015**, *37*, 1271–1277.
17. Wen, S.; Xu, W.Y. Risk analysis on TBM jamming in deep buried tunnel. *J. Yangtze River Sci. Ic Res. Inst.* **2008**, *25*, 135–138.
18. Xiong, Y.; Kong, D.; Cheng, Z.; Wu, G.; Zhang, Q. The Comprehensive Identifification of Roof Risk in a Fully Mechanized Working Face Using the Cloud Model. *Mathematics* **2021**, *9*, 2072. [CrossRef]
19. Xiong, Y.; Yang, S.; Kong, D.; Song, G.; Ma, Z.; Zuo, Y. Analysis on early warning of coal sample failure based on crack development law and strain evolution characteristics. *Eng. Fail. Anal.* **2023**, *148*, 107170. [CrossRef]
20. Li, Y.H.; Tang, X.J.; Yang, S.; Chen, J.W. Evolution of the broken rock zone in the mixed ground tunnel based on the DSCM. *Tunn. Undergr. Space Technol.* **2019**, *84*, 248–258. [CrossRef]
21. Xu, X.; Wu, Z.; Sun, H.; Weng, L.; Chu, Z.; Liu, Q. An extended numerical manifold method for simulation of grouting reinforcement in deep rock tunnels. *Tunn. Undergr. Space Technol. Inc. Trenchless Technol. Res.* **2021**, *115*, 104020. [CrossRef]
22. Wang, X.L.; Yu, W.; Liu, C.X. TBM construction ventilation simulation for deep buried headrace tunnels considering heat transfer in surrounding rock. *J. Hydroelectr. Eng.* **2019**, *38*, 1–13.
23. Zhou, J.J.; Yang, Z.X. Discussion on key issues of TBM construction for long and deep tunnels. *Rock Soil Mech.* **2014**, *35*, 299–305.
24. Qiu, H.; Zhang, F.; Liu, L.; Huan, C.; Hou, D.; Kang, W. Experimental study on acoustic emission characteristics of cemented rock-tailings backfill. *Constr. Build. Materials* **2022**, *315*, 125278. [CrossRef]
25. Ding, Z.; Tang, Q.; Feng, R.; Jia, J.; Li, X.; Huang, X.; Zhang, C. RMA novel technique for determining transverse permeability of sorptive reservoirs. *Geomech. Geophys. Geo-Energy Geo-Resour.* **2022**, *8*, 193.
26. Liu, Q.S.; Huang, X.; Gong, Q.; Du, L.; Pan, Y.; Liu, J. Applicatetion and development of hard rock TBM and its prospect in China. *Tunn. Undergr. Space Technol. Inc. Trenchless Technol. Res.* **2016**, *57*, 33–46. [CrossRef]
27. Ding, Z.; Li, X.; Huang, X.; Wang, M.; Tang, Q.; Jia, J. Feature extraction, recognition, and classification of acoustic emission waveform signal of coal rock sample under uniaxial compression. *Int. J. Rock Mech. Min. Sci.* **2022**, *160*, 105262. [CrossRef]
28. Qi, M.X.; Zhou, Y.L. Study and application of sustained, proportional and speedy (SPS) construction method for TBM tunnel. *Tunn. Constr.* **2018**, *38*, 1860–1867.

29. Ding, Z.W.; Jia, J.D.; Tang, Q.B.; Li, X.F. Mechanical Properties and Energy Damage Evolution Characteristics of Coal Under Cyclic Loading and Unloading. *Rock Mech. Rock Eng.* **2022**, *55*, 4765–4781. [CrossRef]
30. Zhao, J. The application and effect evaluation of reinforcing support design in TBM tunnel construction in unfavorable geologicalsection. *Constr. Des. Eng.* **2019**, *16*, 84–85.
31. Wang, D.J.; He, F.; Wang, Y. Tunnel boring machine (TBM) in coal mine and its intelligen key technology. *J. China Coal Soc.* **2020**, *45*, 2031–2044.