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Challenges and Thoughts on the Development of Large-Diameter Drilling Technology and Equipment

Liu Zhiqiang[1,2], Chen Xiangsheng[2,3], Cai Meifeng[4], Ji Hongguang[4], Song Zhaoyang[1,2]

1. Beijing Coal Mine Construction Company Ltd., Beijing 100013, China
2. National Engineering Research Center of Deep Shaft Construction, Beijing 100013, China
3. College of Civil and Transportation Engineering, Shenzhen University,Shenzhen 518061, Guangdong, China
4. School of Civil and Resource Engineering, University of Science and Technology Beijing, Beijing 100083, China

Abstract: Underground space and resources are crucial for solving the energy, resource, and living space problems faced by mankind. Shafts are throats that extend from the ground into the strata, which require safe, efficient, green, and intelligent construction. In this paper, we analyze the need to develop large-diameter drilling technology and equipment, examine the development status in China and abroad, and consider the challenges faced by China from the perspectives of basic research, applied technology development, high-end equipment manufacturing, and project demonstration. We identify the development directions of shaft construction technology and equipment, and propose that China should establish an intelligent drilling development concept, clarify the development path and tasks of intelligent drilling, establish relevant standards and specifications for large-diameter drilling, and promote the construction of intelligent drilling platforms and demonstration projects to support shaft construction in fields such as mining, hydropower, transportation, and urban construction.
Keywords: underground engineering; shaft construction; mineral exploitation; underground space development and utilization, drilling technology and equipment

1 Introduction

With the rapid development of human society and economic activity, the exploitation and utilization of underground resources and spaces has become an effective way to improve the living environment and support the sustainable development of mankind. As a result, many countries have formulated industrialization, digitization, and intelligent development strategies aimed at exploiting and utilizing underground energy resources [1–2]. As various industries (e.g., energy, mining, hydropower, railway, and urban construction) have developed with the expansion of the scale of construction, innovative endeavors in engineering technology have become highly active. China—a vast country with the capability to effectively exploit mineral resources and utilize underground space—has successfully transitioned from the task of solving the conflict between supply and demand to quality improvement. During the 14th Five-Year Plan period, for the middle and long term, China is committed to transformation and reform to achieve safety, low carbon emissions, and intelligence [3–5].

The shaft is a core structure of underground engineering and construction used to perform various tasks, such as the transportation of minerals, personnel, materials, and equipment; underground ventilation, power supply, and drainage. The application of shafts has expanded from the traditional exploitation of underground mineral resources

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Corresponding author: Liu Zhiqiang, Researcher of Beijing China Coal Mining Engineering Co., Ltd. The main research direction is shaft construction and mechanical rock breaking drilling technology and equipment. E-mail: liuzhiqiang@vip.sohu.com

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to fields such as railway and highway tunnels, urban underground space, hydroelectric power stations, offshore wind power, scientific experiments, and national defense. A large-diameter shaft plays a key role in underground engineering and development. It also provides essential support for major national strategic initiatives aimed at energy and resource security, underground space development and utilization, and deep exploration.

Large-diameter shaft drilling technology and equipment are not only a key research direction in the field of underground engineering construction but also essential for the development of national strategic high-end equipment manufacturing industries [6]. Owing to the continuous changes in national policies for clean, green, and low-carbon energy as well as the requirements of the National Energy Administration, Ministry of Emergency Management, National Development and Reform Commission, and other agencies for the safe, efficient, green, and intelligent construction of mining and other underground projects, conventional drilling, blasting, and rock-breaking technologies must deal with problems such as high safety risks, discontinuous operations, environmental pollution, and severe occupational injuries, which are not in line with the intelligent development trend of mine construction. However, the development of mechanical rock-breaking and drilling technologies and equipment in China remains in the initial stage. Despite the progress in large-diameter shaft drilling machines, raise boring machines, shaft boring machines, and inclined shaft hard-rock boring machines, China's foundation for drilling equipment and technology remains weak and lags behind that of developed countries. Moreover, China still relies on imported components, sensors, and special materials for drilling equipment and vertical shaft sinking machines. This has increased the need to scientifically plan and promote the development, innovation, and application of intelligent drilling technology and equipment, such as large-scale rock-breaking and gravity slag discharge technology, surrounding rock and structure stability control, intelligent machine manufacturing, environmental perception and feedback, and drilling risk prevention and control through the fusion of disciplines such as geology, design, rock and soil, mechanics, machinery, materials, safety, control, and information [6,7]. In this way, China can improve its innovation ability and international competitiveness for large-diameter shaft drilling technology and equipment.

After considering the need to develop large-diameter mechanical rock-breaking and drilling technology and equipment, and comparing the development status both domestically and abroad, this paper presents an analysis of the challenges faced by China in the development of drilling technology and equipment from such perspectives as the research on fundamental scientific issues, and the research and development (R&D) of applied technologies, high-end equipment manufacturing, and engineering demonstration. This paper also describes the development direction of shaft construction technology and equipment, and proposes measures to facilitate the development of underground engineering construction and resources in China.

2 Requirement analysis of large-diameter drilling technology and equipment

2.1 Promoting technological reform of shaft construction

The mining of solid mineral resources and the construction of underground spaces are carried out in stable spatial engineering structures constructed in deep rock bodies using rock-breaking technology and equipment. The access to underground space, the acquisition of mineral resources, and the potential for continuous operations are the basic requirements of underground engineering construction. During the development of large-diameter shaft construction technology, the first technological breakthrough was the replacement of artificial rock-breaking with drilling and blasting technology. Mechanical rock-breaking and drilling technology was the second major technological breakthrough that transformed the blasting and rock-breaking process, which is discontinuous and difficult to control, into a continuous rock-breaking operation with a full-section cutter head or drill bit [8]. Mechanical rock-breaking and drilling technology effectively reduces the number of operators required in a narrow shaft space, serious occupational injuries, environmental pollution, discontinuous operations, and accident risk, and improves efficiency. It can also overcome the technological challenges associated with strata prediction, adverse strata modification, large-scale rock breaking, continuous slag discharge, collaborative excavation and support, perception and control, and risk prevention and control; thus, it opens a new chapter in mechanized, unmanned, and intelligent shaft construction. The improvement of large-diameter shaft drilling technology and equipment not only facilitates underground construction but also solves major engineering and technical problems in the exploitation of deep underground resources in China.

2.2 Supporting the exploitation of national mineral resources

The continuous exploitation of shallow mineral resources in China means that the extraction of resources at depths

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exceeding 1000 m will be inevitable to facilitate the development of the country's mining industry. Statistics show that the domestic coal industry has built more than 40 shafts with depths of over 1000 m. Nearly 20 shafts with depths of over 1000 m have been built in metal mines, seven of which are more than 1500 m deep. The shafts under construction have depths exceeding 2000 m [9,10]. At the 21st Annual Meeting of the China Association for Science and Technology in 2019, 20 major scientific projects and engineering issues that have played key roles in scientific development and technology and industrial innovation were reported, including the full-section tunnel boring technology of kilometer-level deep shaft [11]. Therefore, research efforts on mechanical rock-breaking and large-diameter drilling technology and equipment to deal with the safety and occupational injury-related problems associated with conventional drilling and blasting methods under complex geological conditions (e.g., high ground temperature, high ground pressure, and high water pressure) will provide support for the construction of kilometer-level-deep shafts and ensure the supply of resources.

2.3 Serving the construction of major national underground projects

2.3.1 Development and utilization of urban underground space

The construction and utilization of urban underground spaces in China initially served the purpose of civil defense. However, the construction of deep large-diameter shafts has rapidly increased in cities, including shafts for urban subway tunnels, underground drainage and sewerage, underground parking garages, and underground waste storage and garbage disposal. These construction projects utilize small equipment for excavation, are implemented in a large area, and have low excavation efficiency. The total factor development of urban underground spaces at depths of 60–200 m in China remains at the R&D and design stages. The development of large-diameter shaft drilling technology and equipment can help to solve the urban syndrome, as well as provide technical support for the construction of a resilient city and sponge city.

2.3.2 Construction of hydroelectric power station

Underground powerhouse structures are mainly used for the construction of hydroelectric power stations and pumped-storage power stations in the hydropower industry. These require a large amount of pressure piping, outlet shafts, and ventilation shafts for construction. The shaft depth of pressure pipelines is expected to reach 800 m from the existing shaft depth of approximately 400 m, thus reducing auxiliary construction and optimizing the power station construction system. Large-diameter shaft drilling technology and equipment can be applied to shaft engineering and construction for major water conservation projects, such as national large hydropower stations and pumped-storage power stations, to contribute to the national strategic goals of clean energy development and carbon peak and carbon neutrality.

2.3.3 Construction of deep-buried railways and highway tunnels

During the construction of deep-buried railways and road tunnels, tunnel construction shafts and ventilation shafts are required. Construction shafts are used to increase the working surface and accelerate the construction of the main tunnel. Ventilation shafts ensure the safe operation of the tunnel. At present, the deepest railway shaft recorded in China is the Gaoligongshan Tunnel No. 1, with the main and auxiliary shafts having depths of 762.59 m and 764.74 m, respectively. Conventional drilling and blasting methods were used for construction. Large-diameter shaft drilling technology and equipment can be applied to major deep and large ventilation shaft construction projects in China, such as the Sichuan–Tibet Railway and Xinjiang Tianshan Tunnel, to help fulfill the national strategy of turning China into a country with a strong transportation network and key transportation projects.

2.3.4 Other underground engineering construction

Other underground engineering projects for large-scale scientific experiments are being planned with test shafts approximately 800 m deep. The number, diameter, and depth of shafts for underground engineering projects such as national defense, water diversion tunnels, offshore wind power, underground oil-gas-chemical storage, underground nuclear waste, and CO_2 sequestration, are also increasing annually.

3 Development status of drilling technology and equipment in China and abroad

Research on mechanical rock-breaking and drilling equipment began in China and abroad in the 1960s. Large-diameter shaft equipment for mechanical rock-breaking and drilling includes shaft drilling machines, shaft boring machines, raise boring machines, and inclined shaft hard-rock boring machines. Given that the performance and manufacturing capacity of drilling equipment are vital to the development of drilling technology, this paper elaborates on the drilling equipment and engineering practices suitable for various geological and engineering conditions.

3.1 Shaft drilling machine

In the mid-20th century, the CSD300 (Hughes Tool Co., USA) and L40 (Würth Group, Germany) were the most advanced shaft drilling machines. However, restrictions on materials, processing and manufacturing capacities, and economic cost have hindered the development of mechanical rock-breaking and drilling technology. At the end of the 20th century, changes in the mining industry forced most countries to suspend their R&D on this technology or shift their focus to other technologies, such as tunnel boring machines (TBMs).

To address the difficulties of shaft construction in water-rich deep alluvium in eastern China, the Beijing China Coal Mine Engineering Co., Ltd. together with some Chinese enterprises and universities conducted research on shaft drilling methods with the support of the National Key Technologies R&D Program of China during the 7th Five-Year Plan, 10th Five-Year Plan, and 11th Five-Year Plan periods, respectively. On the basis of foreign drilling machines, they upgraded the L40/1000 drilling machine and developed large-diameter shaft drilling machines, such as AS-12/800 and AD130/1000, with independent intellectual property rights protection [12]. They also developed the rapid drilling method called “one-step shaft excavation” with a diameter of less than 7.7 m, and the “one-step shaft enlargement” with a diameter of 10.8 m. By achieving a maximum drilling depth of 660 m, the shaft drilling technology in China reached new heights and achieved a leading position in the international shaft drilling technology industry. This shaft drilling technology has the advantages of high mechanization, automatic drilling control, and unmanned underground operation, which have been gradually applied to the drilling engineering of offshore wind power pile foundations. ZDZD-100, a fully hydraulic shaft drill rig developed by the China Pingmei Shenma Energy and Chemical Group Co., Ltd., occupies a leading position internationally in terms of drilling capability and drilling diameter. It is being tested for one-step shaft excavation at the Kekegai Coal Mine in Shaanxi Province with a diameter of 8.5 m and depth of 538 m.

3.2 Raise boring machine

Herrenknecht AG of Germany, Redpath of Canada, and Tri-Tech International Investment, Inc. of Australia, are committed to the R&D of raise boring machines and related technologies. They developed the RBR900 and G330SP, the largest raise boring machines with a designed drilling depth of up to 2000 m and a reaming head diameter of 1–8 m. Since the 1980s, Beijing China Coal Mining Engineering Co., Ltd. has been developing the LM series and BMC100–BMC600 series of raise boring machines, which are suitable for underground shaft construction under various stable strata conditions. The company has achieved a maximum drilling diameter and drilling depth of 6 m and 592 m, respectively [13]. The intelligent control BMC1000 series of raise boring machines developed by the company has a designed drilling diameter of 7 m and a designed drilling depth of up to 1000 m. The machines have independent intellectual property rights protections for their core performance and mature technologies. With their modular design and compactness, these machines can maintain flexible operations in narrow sites. Therefore, raise boring machines can be applied to underground engineering construction, indicating the significant progress in the technology and manufacturing of large-diameter raise boring machines in China.

3.3 Shaft boring machine

In the 1960s, countries such as the United States and Germany began to research full-section and partial-section shaft boring machines. Würth of Germany developed a partial-section shaft boring machine with vertical slag discharge called the SB-VI-580/750. Herrenknecht AG of Germany developed a boom-type rock-breaking shaft boring machine with vertical slag discharge, and proposed the concept of a roller-type rock-breaking shaft boring machine with vertical slag discharge [14–16]. Robbins of the United States developed the 241SB-184 shaft boring machine with a “ω-shaped” bit structure. Genie Industries of the United States developed the VDS400/2430 shaft boring machine with a spherical bit structure [17]. To date, foreign-made shaft boring machines have a tunneling diameter of approximately 8.0 m and a tunneling depth of approximately 700 m, with a relatively low tunneling speed and high cost.

During the 12th Five-Year Plan period, the Beijing China Coal Mining Engineering Co., Ltd. began a research program called the *Development of Mine Shaft Boring Machine* under the National High-tech R&D Program (863 Program). It developed the first shaft boring machine called the MSJ5.8/1000/1.6D, which adopted a full-section cone drill bit to break rocks and a navigational drill for slag discharge. In 2020, the first slag-discharging shaft boring

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machine was used in an industrial drilling test conducted at the Yili River Hydropower Station in Yunnan Province. An outlet shaft project with a drilling depth of 282.5 m, a guide hole diameter of 1.4 m, and a tunneling diameter of 5.8 m was completed [18]. The China Railway Engineering Equipment Group Co., Ltd. developed a full-section hard-rock shaft boring machine called the SBM/1000, which adopted a full-section cutter head rock-breaking and mechanical slag-discharge mode. At the end of 2021, the company completed the industrial tests on shaft engineering at the Zhejiang Ninghai Pumped Storage Power Station, with a drilling depth of approximately 198 m and a drilling diameter of 7.83 m. The CCCC Tianhe Mechanical Equipment Manufacturing Co., Ltd. developed a super large-diameter hard-rock shaft boring machine called Shouchuang, which adopted a full-section cutter head rock-breaking and semi-flooded shaft fluid-slag discharge mode. At the end of 2021, the machine was used in the No. 2 Shaft of the Shengli Tunnel, Tianshan, Xinjiang, with a designed drilling diameter of 11.4 m. The development and application of related products indicate that China has mastered the technical system of shaft boring machines. In 2021, the Ministry of Science and Technology organized and approved a special project called the “Key Technology and Equipment of Full-Section Hard-Rock Boring Machine for Kilometer-level Deep Shaft.” The vertical shaft sinking machine (VSM) designed for Chinese cities is in the design and development stage. The purchase of foreign VSM equipment and technical services results in high costs. In 2020, China introduced a caisson-type shaft boring machine called the VSM12000 (Herrenknecht AG, Germany), which adopts partial-section rock cutting and diving-type pump-suction reverse-circulation slag discharge. The caisson-type underground parking garage project in Jianye District, Nanjing City, China, was completed with a maximum excavation depth and drilling diameter of 68 m and 12.8 m, respectively.

3.4 Inclined shaft boring machine

The full-section hard-rock TBM has become an important equipment for the construction of urban subways, railway tunnels, diversion tunnels, and other infrastructure. It can solve problems such as the high risk and labor intensiveness of conventional drilling and blasting methods as well as improve the poor rock-breaking ability of comprehensive mechanized TBMs and the low efficiency of hard-rock tunneling to a certain extent. Statistics show that the tunneling speed of a TBM could be 3–10 times that of drilling and blasting methods, and 2–8 times that of comprehensive mechanized tunneling methods. This highlights its advantages of reducing manpower; improving efficiency, safety, and reliability; decreasing economic costs, and protecting the environment. In China, TBM construction technology is mainly applied in roadway or tunnel excavations, while more TBM inclined shaft engineering practices are carried out abroad. The drilling diameter of the TBM in inclined shafts ranges from 3 to 10 m, with an uphill angle greater than 37°, downhill angle less than 30°, and a maximum drilling length of 1010 m. Statistics show that there are 85 inclined shaft projects around the world that use TBMs in construction; over 60 of these are pumped-storage power stations [19].

In China, the application of TBMs in inclined shaft construction under complex conditions such as large slopes, long distances, and deep burial is in the early stages. In the demonstration project under the National Key Technologies R&D Program of China during the 11th Five-Year Plan period called the “Research and Demonstration of Key Technologies for Long-Distance Inclined Shaft Construction in Shield Tunneling Coal Mine,” the single-shield TBM boring machine developed by the China Railway Construction Heavy Industry Co., Ltd. was used to tunnel the No. 2 auxiliary shaft of the Shendong Bulianta Coal Mine with a continuous downhill angle of 5.5°. The TBM tunneling length is 2718.2 m, while the diameter of the excavation is 7.62 m. The average monthly tunneling distance was 546 m. In 2021, the ZTT7130 open-type full-section TBM developed by the China Railway Construction Heavy Industry Co., Ltd. was adopted for the main and auxiliary inclined shafts of the Kekegai Coal Mine of the Shaanxi Yanchang Petroleum (Group) Co., Ltd. The designed inclination angle of the main inclined shaft was 5.6°, the TBM tunneling distance was 5040.9 m, and the tunneling diameter was 7.13 m. The designed inclination angle of the auxiliary inclined shaft was 6°, and the TBM tunneling distance was 5041.3 m, making this the longest inclined shaft for TBM tunneling in coal measure strata in China [20].

4 Challenges facing the development of drilling technology and equipment in China

4.1 Engineering scenarios and market environment are not well accepted

The drilling and blasting of rocks and small-scale mechanical mining have long played a key role in mine and underground engineering construction. Owing to factors such as economy, efficiency, and reliability, many construction enterprises have limited knowledge and low acceptance of new large-diameter shaft drilling technology, which makes it difficult to replace mechanical rock-breaking drilling technology and equipment. The complexity and uncertainty of large-diameter shafts crossing the strata has led to stringent safety requirements for large-diameter drilling. The centralized control and collaborative operation of multiple systems in the drilling process are also difficult. Moreover, cases that require drilling engineering applications are limited; hence, the feedback from the market is insufficient. As a result, research institutes and enterprises are unwilling to actively participate in the development of drilling technology and equipment. This hinders the improvement of the function and performance of drilling technology and equipment, and prevents technological and equipment innovations from meeting the development needs of underground engineering construction.

4.2 The industrial chain of large-diameter drilling technology and equipment is not perfect

China Coal Technology & Engineering Group Co., Ltd, China Coal Mine Construction Group Co., Ltd, and Luoyang CITIC Heavy Industries Co., Ltd. conducted research on mechanical drilling technology and equipment in China. Chinese companies, such as China Railway Construction Heavy Industry Co., Ltd., China Railway Engineering Equipment Group Co., Ltd., and CCCC Tianhe Mechanical Equipment Manufacturing Co., Ltd., had a late start on their research on large-diameter drilling equipment manufacturing. They shifted from the development of TBMs or road headers to the development of shaft drilling machines. Owing to the weak core technologies and independent innovation ability, they focused on the introduction and upgrading of foreign equipment. The key components of drilling equipment, such as main bearings, hydraulic parts, electrical control components, and the design technology of overall integration have been developed domestically. Although the dependence on imported core components has decreased, domestic companies still fall behind foreign companies owing to factors such as the insufficiency of new materials and processing technologies. Many equipment manufacturing companies are unfamiliar with the engineering adaptability of drilling technology and equipment. Thus, the design and R&D of basic drilling theories, technologies, processes, and equipment are still undertaken by research institutes and universities. The incomplete drilling technology and equipment industrial chain has hindered the development of drilling technology and the improvement in performance of manufacturing equipment.

4.3 The intelligent drilling technology and equipment are in the early stage

Intelligent drilling represents the transition from mechanized and informatized to intelligent shaft construction. At present, the basic theory of intelligent drilling is weak, and bottlenecks in areas such as core key technologies and intelligent equipment manufacturing capability have yet to be overcome. To a certain extent, existing mechanical rock-breaking and drilling technology and equipment continue to serve as a replacement for blasting technology or an extension or replacement of manual operations. Owing to the complexity, particularity, and variability of geological conditions, as well as the autonomous learning opportunities brought about by the low repetition of equipment operation, the deep learning and analysis of intelligent drilling equipment presents a challenge, along with the research, development, and reliable operation of the decision-making system. As a result, it is difficult to realize independent decision-making and intelligent control in areas such as strata perception, drilling equipment operation, and shaft structure stability. Existing intelligent drilling monitoring and analysis systems have disadvantages such as “valuing monitoring over control” and “strong management and weak technology.” The main problem faced by intelligent shaft construction is realizing the intelligent analysis and decision-making of the ternary system consisting of environmental equipment, simulation, and judgment feedback. Because intelligent drilling is in the initial stage, the top-level design and development path of intelligent drilling, including key technologies, core equipment, R&D platforms, disciplines, standards, talent teams, and demonstration projects, is far from perfect.

5 Key development direction of shaft construction technology and equipment

To transform China’s underground engineering construction from quantity-oriented to quality-oriented, and improve the competitiveness of core drilling technology and high-end domestic equipment, we should follow the research ideas of “basic theory–application technology–whole equipment–drilling technology–engineering demonstration”; solve key technological problems such as drilling strata control, efficient drilling, structure stability, and disaster prevention and control; and develop efficient, reliable, and intelligent drilling equipment and supporting systems that can meet the need for safe, fast, intelligent and green shaft construction in the field of underground engineering.

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5.1 Geological guarantee for drilling engineering

To a large extent, the complexity of geotechnical engineering problems, particularly the construction of kilometer-deep shafts, is dependent on the geological conditions of the shaft crossing. To realize safe, efficient, and green drilling with a high reliability, high efficiency, and intelligent mechanical rock-breaking equipment under complex geological environments and working conditions, it is necessary to address geological transparency and provide the geological safety guarantee of transparent geology, target modification, and active disaster control for dry-shaft boring equipment. Significant efforts should be made to develop methods for the fine *in-situ* detection of rock mass, lithology identification, and surrounding rock classification based on multiple detection measures; solve key technical issues such as remote dynamic detection during drilling, rock mass parameter perception, risk identification, and comprehensive premodification of strata; and improve the geological risk evaluation and prevention mechanism of large-diameter drilling.

5.2 Breakthroughs in drilling technology

Currently, drilling machines (e.g., shaft drilling machines, shaft boring machines, raise boring machines, and inclined shaft boring machines) are equipped with their own drilling technology and processes. However, while these mechanical rock-breaking machines are used for drilling construction, all of them follow four principles: efficient rock-breaking, continuous slag discharge, accurate drilling, and surrounding rock stability [7]. To solve the adaptability problem of large-diameter drilling technology under the multifield-coupling condition, theories and methods should be developed, such as spatial layout design for mechanical rock-breaking and drilling; parallel operation technology for drilling, slagging, surrounding rock, and strata modification; and drilling risk control technology. To deal with the difficulties in breaking hard rock, repeated breaking, and surrounding rock disturbance, technical problems such as the large-scale breaking of hard rock through multicutter cooperation and new rock-breaking methods, mechanical or fluid continuous slagging against gravity, drilling support, and permanent support should be solved.

5.3 Improvement of equipment design and manufacturing capability

To accommodate the characteristics of complexity, variability, and uncertainty of shaft crossing strata, we should adopt the design concept of material–structure–performance integration and the design–manufacturing–operation entire process collaboration, and develop a large-diameter drill rig with intelligent perception, centralized control, and strong adaptability. In addition, we should focus on dynamics modeling under multisource dynamic load excitation, the analysis and optimization of system coupling dynamics, the whole machine assembly, and the optimized spatial layout. We should also develop key functional systems such as rock-breaking and drilling-machine role perception feedback, advanced detection of unqualified geology, revolving design–manufacturing–operation tunneling design–manufacturing–operation supporting coordination, and high-precision equipment attitude control systems. In this manner, we can build intelligent high-end drilling equipment and supporting systems that are lightweight with high performance, low energy consumption, high efficiency, and high reliability.

5.4 Operation, maintenance, and early warning of the drilling system

During the underground large-diameter drilling process, we should monitor the operation state of the drilling equipment and the stability of the surrounding rock and supporting structure in real time, and develop technical measures for disaster prevention and mitigation. We should also focus on the intelligent diagnosis and early warning of the operational reliability and stability of intelligent drilling systems, including detection, tunneling, slagging, supporting, mining, guiding, cooling, drainage, and ventilation. Moreover, we must conduct monitoring and risk control of the surrounding rock and supporting structure; build a multidimensional data-fusion network transmission system and an intelligent terminal platform for the drilling process; develop quick escape technology for extremely harsh conditions inside the shaft; respond promptly to risks; and reduce economic losses.

6 Suggestions

6.1 Establishing the development concept of intelligent drilling

The development of large-diameter drilling technology and equipment for underground engineering in China should follow the principles of safety, efficiency, green, and intelligence. The government, industries, enterprises, and research institutes should work together in undertaking key national projects or programs. Universities and enterprises should play a major role, while competent departments of the government and industry should provide the necessary services. Guided by market demands, we should increase investments in special projects, formulate supporting policies, and improve the technological industrial chain. Moreover, we should develop a high-power intelligent drilling rig and supporting equipment; solve problems related to the collaborative control technology of the large-diameter drilling system under complex geological conditions; and build an informatized, unmanned, and intelligent large-diameter drilling system based on information fusion, digital logic models, intelligent control, and other technologies. We also need to develop guarantee measures with comprehensive coverage, key points, and long-term effectiveness in areas such as intelligent drilling organizational structure, control mode, management method, operation mode, and post-responsibilities. We should actively integrate existing and potential resources, and promote basic research on intelligent drilling, key technological breakthroughs, and intelligent equipment manufacturing in China to meet the need for improved efficiency and realize high-quality development.

6.2 Determining the development paths and tasks of intelligent drilling

According to the development concept of intelligent drilling in China, we should conduct top-level planning of intelligent drilling, solve the key scientific problems, address technological bottlenecks, and determine the development paths and key tasks of intelligent drilling technology and equipment. At present, large-diameter shaft drilling products in China are far from diverse. Considering the development trends in underground shaft construction from shallow to deep, and from small-diameter to large-diameter drilling, we must diversify our products to adapt to different strata and engineering conditions in the future. In addition, we should develop large-diameter drilling technology and equipment systems and development frameworks according to various types, stages, and layers. For the overall intelligent drilling system in underground engineering construction, we should carry out a feasibility analysis and process research of drill rigs based on the drilling depth and diameter, and develop theoretical methods for drilling equipment selection and spatial layout. We should overcome technological challenges, such as fine strata exploration and strata premodification, large-scale rock breaking and continuous slag discharge, surrounding rock stability, and tunneling-supporting coordinated control. In addition to the technologies for drilling equipment environment perception, decision-making, and attitude control, we should develop intelligent drilling equipment that are lightweight with high performance, low energy consumption, high efficiency, and high reliability. We should make breakthroughs in real-time monitoring and early warning technology for drilling equipment and surrounding rock support structures; build disaster prevention and mitigation and whole-process risk control systems for intelligent drilling; and realize intelligent perception, precision drilling, and risk control for large-diameter drilling.

6.3 Formulating and improving standards and specifications related to large-diameter drilling

To lead and promote the high-quality development of the industry, we should establish sound, transferrable, and forward-looking standards. At present, large-diameter drilling technology and equipment are applied in industries such as coal mines, metal mines, rail transportation, urban underground space, hydroelectric power, and offshore wind power. Owing to differences in engineering functional properties and strata conditions, the requirements of large-diameter drilling technology and equipment also vary. Therefore, various industries have established relevant standards and specifications. For example, in the coal industry, standards and specifications for raise boring and shaft drilling have been established. However, standards and specifications for shaft boring or inclined shaft boring are still lacking. Some industries lack standards and specifications for large-diameter drilling; therefore, construction enterprises have rejected large-diameter drilling technology. The lack of standards and specifications for intelligent drilling has significantly hindered the development of large-diameter drilling equipment. Therefore, it is necessary to formulate standards and specifications, such as technical terms, technologies, equipment, inspection and monitoring, and quality acceptance; issue national standards for general technologies; and promote intelligent drilling from the initial to the middle and advanced stages.

6.4 Facilitating the construction of intelligent drilling platforms and demonstration projects

There are only a small number of large-diameter drilling equipment manufacturers in China, and it is difficult for a single enterprise to conduct independent R&D on high-quality intelligent drilling technology and equipment. With the approval of the General Office of the National Development and Reform Commission, the “National Engineering Research Center for Deep Mine Construction Technology” is the only national R&D platform devoted to shaft

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construction in China. The R&D platform was built by one scientific research institute, one national safety certification center, three universities, and three production and construction enterprises. Therefore, equipment manufacturers, equipment application enterprises, research institutes, and universities should strengthen their cooperation, increase their investments in basic R&D, improve engineering innovation and decision-making, and facilitate the application of scientific research achievements. All parties should share their achievements with an innovation-oriented mindset, a coordinated pathway, green mission, and an open vision.

Given problems such as the short industrial chain, scattered distribution of R&D and manufacturing resources, and the low-level cross-disciplinary integration, we should conduct overall planning at the national level, integrate advantageous resources, provide suggestions on developing intelligent drilling for underground engineering, and build a comprehensive technological innovation platform that covers basic theory, common technology, equipment development, and engineering demonstration. In addition, we will support various enterprises in establishing R&D platforms, such as innovation centers, technology centers, and industrial design centers; and strengthen international exchanges and cooperation when necessary. Colleges and universities should also offer drilling technology disciplines at different levels and build a team of technical experts specializing in research, development, design, and construction to promote the development of large-diameter intelligent drilling technology and equipment in China.

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