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Overview of the Research Status and Development Trends of Key Technologies in Trenchless Horizontal Directional Drilling

Jiaorao Li [1], Xiaoqiang Liang [1, 2, *], Yuyang Cao [1], Yimin Peng [1] and Pengrui Yu [1]

[1]School of Civil Engineering, Hunan City University, Yiyang 413000, China

[2]Hunan Engineering Research Center of Structural Safety and Disaster Prevention for Urban Underground Infrastructure, Hunan City University, Yiyang 413000, China

*liangxiaoqiang@hncu.edu.cn (Corresponding author)

Abstract

With the acceleration of urbanization, the demand for environmental protection, high efficiency, safety and economic construction technology for urban underground pipeline construction is growing. As the core method of trenchless technology, horizontal directional drilling (HDD) has attracted much attention because of its high construction speed, low cost and low environmental disturbance. However, under complex geological conditions, the key problems such as bit guidance and control, hole wall stability maintenance, mud treatment and environmental protection still need to be solved. This paper systematically reviews the research progress of key technologies of trenchless horizontal directional drilling equipment from two aspects of theoretical analysis and engineering practice, focusing on the development history of guided drilling technology (including the research status at home and abroad), the influence mechanism and control method of hole wall stability, and the frontier exploration of equipment intelligence, automation and green construction. By means of literature statistics, numerical simulation, physical test and field monitoring, the application status of trenchless technology in pipeline laying, geological exploration and other fields is comprehensively reviewed, and the solution ideas are put forward for the problems existing in the construction process of complex formation, such as deviation, stuck drilling and instability. This review not only provides a theoretical basis for further improving construction efficiency and engineering quality, but also looks forward to the development trend of intelligent and green equipment in the future.

Keywords

Trenchless Technology, Horizontal Directional Drilling, Bit Monitoring, Hole Wall Stability, Equipment Technology.

1. Introduction

In recent years, under the dual promotion of national policy and economic development, trenchless technology has been widely used in urban underground pipe gallery, gas pipeline, power and communication fields [1]. As an important means of trenchless construction, horizontal directional drilling technology has obvious advantages in reducing environmental disturbance, shortening construction period and reducing engineering cost. At the same time, the guiding control, real-time monitoring and the stability of hole wall in complex stratum will directly affect the safety and construction quality of the project. The purpose of this paper is to systematically analyze the development status, existing problems and future trend of the key technology of horizontal directional drilling equipment from the angle of theory and practice, so as to provide reference for technical improvement and engineering application in related fields.

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2. Research Status of Key Technologies of Trenchless Horizontal Directional Drilling

2.1. Distribution and hot spots of academic research

Based on the analysis of the publishing trend, key word distribution and author distribution of relevant academic papers in recent ten years, this paper aims to summarize the research hotspot and development trend in the field of trenchless horizontal directional drilling. The specific research method is as follows: using "trenchless technology" and "horizontal directional drilling" as key words on China National Knowledge Infrastructure (CNKI), we searched 1805 Chinese and English journal papers published during 2015-2024 (see Fig. 1), and statistically analyzed their publication time, key words and author distribution. The results show that the number of papers published in this field is increasing year by year, especially in the past five years, the number of papers published in China remains high. Key words focus on horizontal directional drilling, trenchless technology, pipe jacking, trenchless construction, etc. The main researchers focus on universities and research institutes (see Fig. 2). This provides a useful reference for the research and application of China's trenchless horizontal directional drilling technology, and also provides an important reference for the follow-up related research.

In addition, the author searched a total of 300 papers in the general database by searching the keyword “Trenchless Horizontal Hirectional Hrilling” on CNKI, and the proportion of topics is shown in Fig. 2 through the visual analysis results of the keywords of the papers by Vosviewer.

From Fig. 2, the results of the above literature search correspond to the current application of trenchless and horizontal directional drilling in engineering. Trenchless technology is most closely related to such topics as horizontal directional drilling, pipeline repair, quality control, municipal

engineering, etc. There are enough literatures on trenchless technology for reference. In addition, it can be known that trenchless technology is developing towards pipeline repair and pipeline drilling under complex strata[2-4].

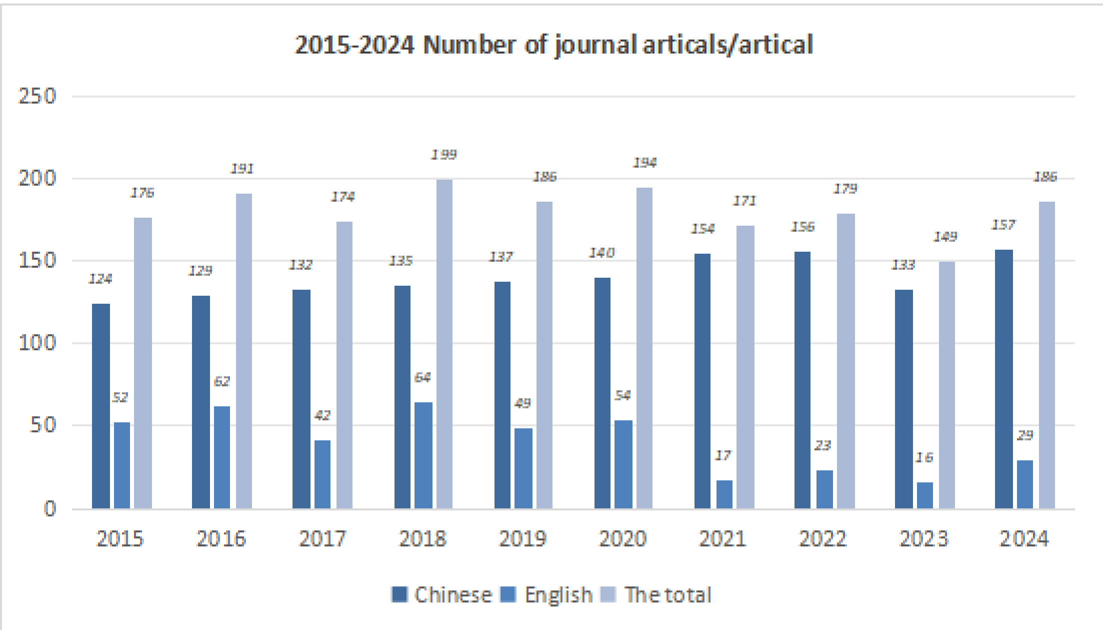

Fig. 1 Paper publication trend chart related to trenchless horizontal directional drilling

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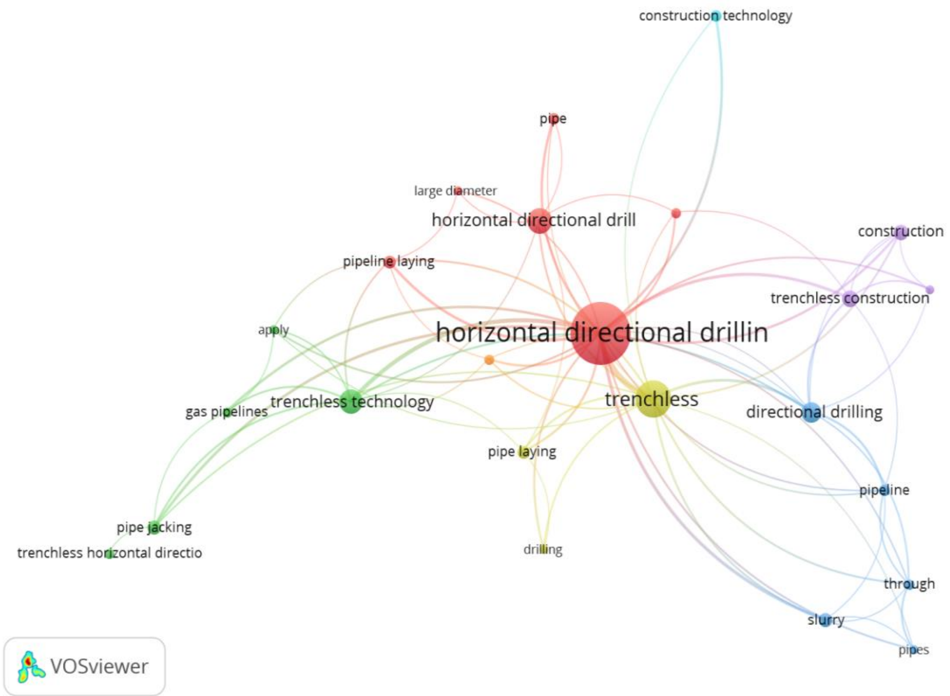

Fig. 2 Trenchless and HDD by research topic paper keyword distribution map

At the same time, the results of visual analysis of the authors are shown in Fig. 3. As shown in the figure, Wu Xiaoming and Ma Baosong of China University of Geosciences and Sun Pinghe of Central South University have conducted research on the key equipment and development trend of non-excavation horizontal directional drilling [5-10]. Relevant documents can prove that the application research of non-excavation technology in China is quite sufficient.

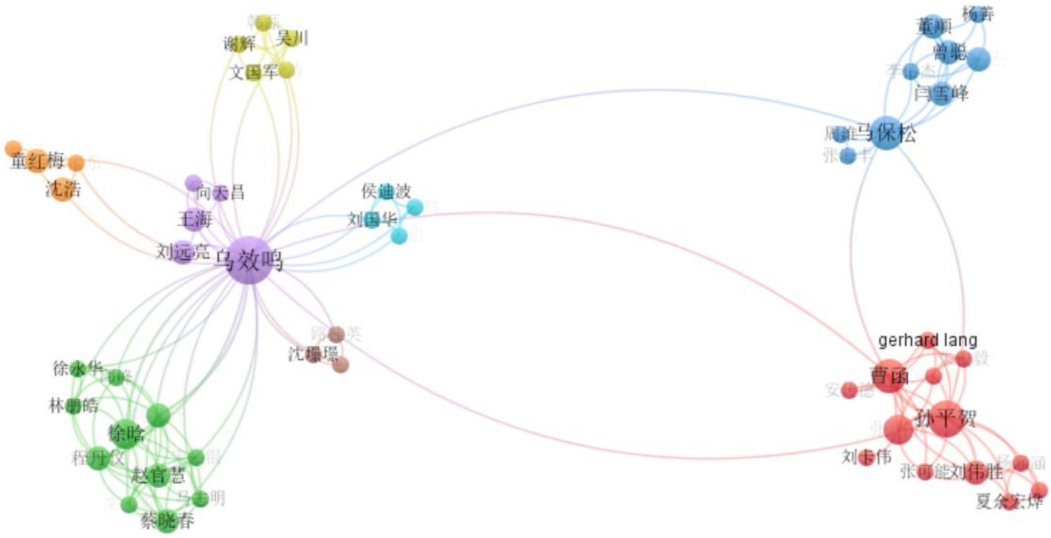

Fig. 3 Trenchless and horizontal directional drilling by research topic paper author distribution map

2.2. Development history of horizontal directional drilling technology

2.2.1. Overview of foreign development

Since the directional drilling test was carried out in the coal mine field in Britain in 1957, foreign countries have accumulated experience in the theory and practice of directional drilling [11]. In 1964, the United States began to systematically study directional drilling technology, and

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achieved remarkable results in coal mine gas extraction, geological anomaly detection and other fields [12]. In 1971, Martin Cherrington of California first proposed the concept of horizontal directional drilling by combining oil drilling technology with trenchless pipeline construction. At the end of the 20th century, with the introduction of MWD technology and rotary steering system (see Fig. 4), foreign horizontal directional drilling technology realized a leap from experiential construction to intelligent control, greatly improving drilling accuracy and efficiency [13].

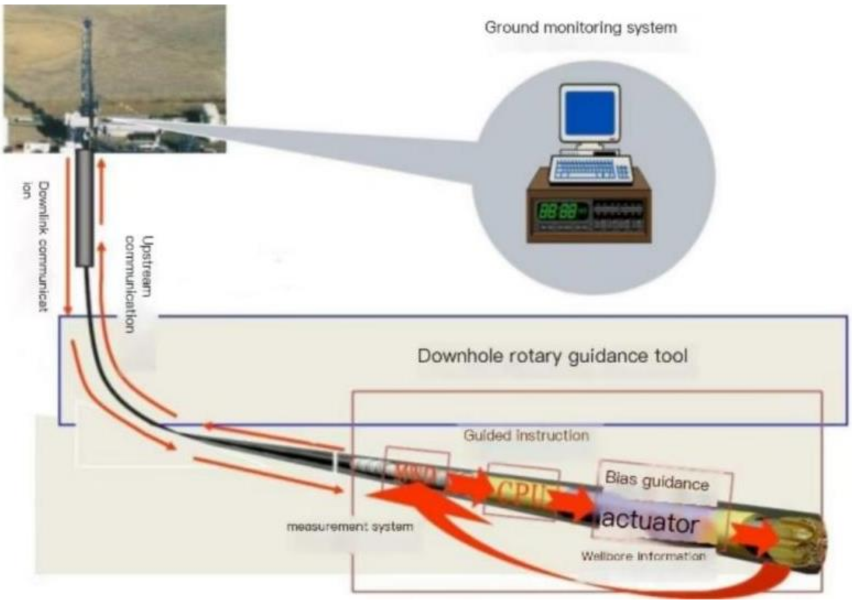

Fig. 4 Trenchless rotary steerable system

2.2.2. Domestic development status

Horizontal directional drilling technology started late in China, but developed rapidly. From the introduction of horizontal directional drilling crossing technology in the early 1980s to the realization of directional crossing under ultra-long distance and complex formation conditions in recent years, China has formed a relatively complete technical system [14,15]. In 2019, Xi 'an Research Institute of China Coal Science and Industry Group completed an ultra-long directional drilling along the coal seam with a main hole depth of 3353m in Bade Coal Mine of Shendong Coal Group, refreshing the world record for downhole directional drilling in China. In the same year, Sinopec Sales South China Branch completed the directional crossing construction of 4017m in Zhanjiang Beihai Pipeline project [1]. At present, the main research in China is focused on real-time monitoring of drill bit, optimization of guidance system and data communication, and gradually moving towards full closed-loop intelligent control and automated construction. However, there are still shortcomings in high-precision positioning, trajectory control in complex geological environments and the stability of whole-process data transmission, which need to be further broken through.

2.3. Research on stability of horizontal directional drilling wall

Borehole wall stability is a key technical problem in horizontal directional drilling construction, which is directly related to engineering safety and construction efficiency. In recent years, scholars at home and abroad have extensively studied the mechanism and control methods of hole wall instability from the perspectives of theoretical analysis, numerical simulation, physical test and field monitoring [16,17].

2.3.1. Theoretical research and mechanism analysis

Based on the mechanics, elastic-plastic and viscoelastic constitutive theories of porous media, many studies have analyzed the stress field, failure mode and maximum allowable drilling fluid pressure of hole wall [18]. By reasonably simplifying complex engineering models, the analytical method can provide intuitive and convenient guidance for drilling design, but it still has limitations when dealing with actual complex formations.

2.3.2. Numerical simulation and experimental research

It has become an important means to study pore wall stability to establish a model using finite element method and fluid-solid coupling method [17,19]. These simulation methods can not only predict the stress redistribution and fluid intrusion of the formation during drilling, but also optimize the drilling parameters. At the same time, the laboratory model test and in-situ monitoring experiment provide the verification basis for the numerical simulation, which is helpful to deeply understand the internal mechanism of hole wall instability.

2.3.3. Information monitoring and real-time monitoring

In recent years, information technologies such as ultrasonic detection, ground magnetic beacon positioning(see Fig. 5) and wireless transmission have been gradually introduced into horizontal directional drilling construction to realize real-time monitoring of drilling trajectory, changes in aperture and hole wall status [20]. The real-time positioning system based on the ground magnetic beacon, by combining with the drilling tool measurement while drilling technology, significantly reduces the cumulative error and improves the guiding accuracy. In addition, new drilling tools such as push-back steering systems are also being improved, providing more technical options for bit steering control [21].

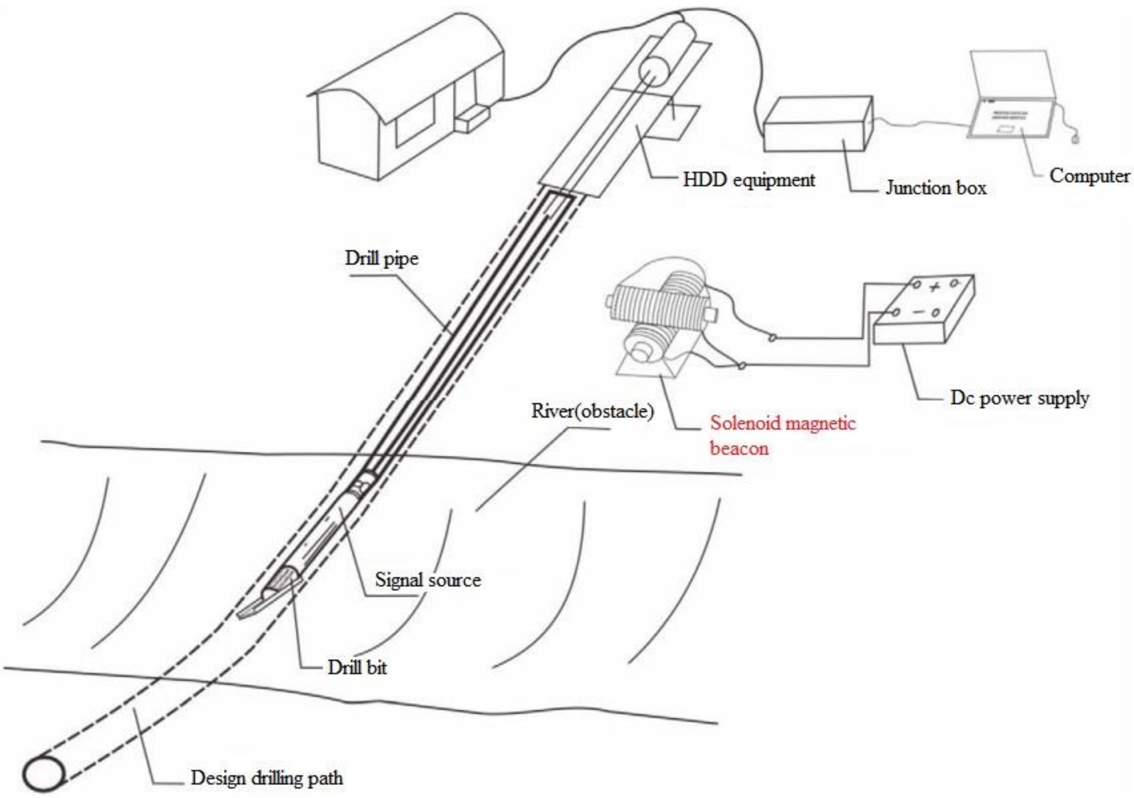

Fig. 5 Ground magnetic beacon system

3. Automation, intelligence and green development trend

3.1. Automation and intelligent technology

With the rapid development of artificial intelligence, Internet of Things and big data technology, trenchless horizontal directional drilling equipment is moving towards full automation and intelligence [22,23]. Technologies such as automated construction machinery, automatic control of guidance systems, intelligent sensor data fusion and real-time decision-making are gradually being applied to rig operation and guidance control, which is expected to greatly improve construction efficiency and engineering safety. At present, some enterprises have developed a bit trajectory planning system based on intelligent algorithms, but there are still technical bottlenecks in intelligent monitoring, fault self-diagnosis and self-regulation of the whole process.

3.2. Green construction

The concept of green construction requires the realization of resource saving, environmental protection and construction efficiency improvement in the whole life cycle of the project. Compared with traditional excavation laying, trenchless horizontal directional drilling technology has the advantages of low construction disturbance, low noise and high environmental protection. The application of new environmentally friendly drilling fluids, corrosion-resistant high-strength plastic pipes (such as PE pipes) and energy-saving construction equipment is promoting the transformation of this technology to green construction [24]. At the same time, the green remanufacturing and equipment maintenance technology based on the whole life cycle also provides technical support for the sustainable development of tunnel and underground engineering equipment.

4. Key problems and countermeasures of complex strata

At present, trenchless horizontal directional drilling under complex formation conditions mainly faces some key problems, such as bit steering and trajectory control, hole wall stability maintenance, data transmission and intelligent monitoring.

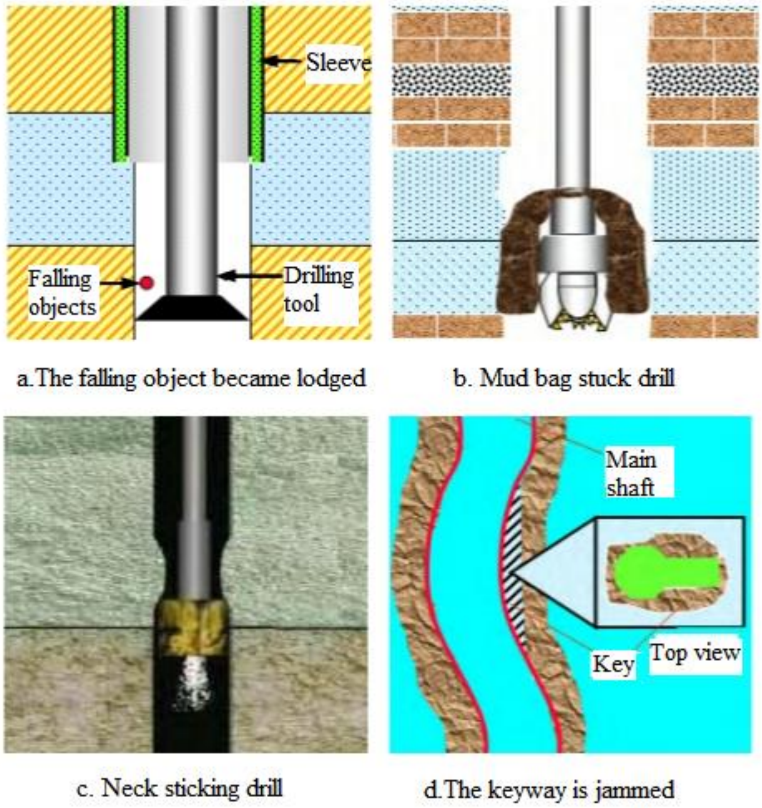

Fig. 6 Drilling problems under complex geological conditions[1]

4.1. Bit guidance and trajectory control

Under complex formation conditions, the steering and trajectory control of drill bit is the key to ensure the smooth progress of engineering. Variable geological conditions, such as

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alternating soft and hard formations, faults, cracks（see Fig. 6）, etc., can easily cause the drill bit to deviate from the

predetermined trajectory. In order to deal with this problem, it needs to be optimized from the following aspects:

Guidance system optimization: The existing guidance system mainly relies on sensors such as magnetometers and gyroscopes to detect the orientation and inclination of the bit. In complex formations, these sensors can be affected by formation magnetism and other disturbances, resulting in measurement errors. Therefore, more accurate and anti-jamming guidance systems need to be developed, such as those based on inertial navigation systems (INS) or laser guidance technology[25,26].

Real-time monitoring technology: real-time monitoring of the position and trajectory of the drill is an important means to ensure that the drill moves forward according to the predetermined path. At present, the commonly used monitoring techniques include measurement while drilling (MWD) and well logging while Drilling (LWD). However, these technologies may face problems such as data transmission delay and signal attenuation in complex formations. Therefore, it is necessary to develop more stable and efficient real-time monitoring technology, such as real-time monitoring system based on optical fiber sensing technology.

Intelligent trajectory correction: When the drill deviates from the predetermined trajectory, the traditional correction method relies on manual intervention, and the efficiency is low. Through the introduction of artificial intelligence (AI) and machine learning (ML) techniques, intelligent correction of the bit trajectory can be achieved. For example, based on historical data and real-time monitoring data, the AI system can predict the deviation trend of the bit and automatically adjust the drilling parameters to ensure that the bit is on a predetermined trajectory.

4.2. Hole wall stability maintenance

Hole wall stability is one of the key factors for the successful application of HDD technology in complex formations. Different formation parameters (such as lithology, pore pressure, ground stress, etc.) have significant effects on hole wall stability, so it is necessary to control drilling fluid pressure and drilling parameters reasonably during drilling.

Drilling fluid pressure control: drilling fluid pressure is an important factor to maintain hole wall stability. In complex formations, too high drilling fluid pressure may lead to formation rupture, while too low pressure may lead to hole wall collapse. Therefore, drilling fluid pressure needs to be adjusted in real time according to formation parameters [27,28]. For example, in high-pressure formations, increasing drilling fluid density is required to equalize formation pressure. In low-pressure formations, the drilling fluid density needs to be reduced to prevent hole wall collapse.

Optimization of drilling parameters: drilling parameters (such as drilling rate, weight on bit, rotational speed, etc.) also have an important impact on hole wall stability. In complex formations, a high drilling rate may cause wall instability, while a low drilling rate may increase drilling time. Therefore, drilling parameters need to be optimized according to formation parameters. For example, in soft formations, the drilling rate can be appropriately increased; In hard formations, the drilling rate is reduced to prevent bit wear and wall instability.

Hole wall reinforcement technology: In strata with poor hole wall stability, hole wall reinforcement technology can be used to enhance hole wall stability. For example, the hole walls are reinforced by injecting chemical grout or cement slurry, or casing technology is used to protect the hole walls.

4.3. Data transmission and intelligent monitoring

Whole-process dynamic monitoring is an important means to ensure the successful application of HDD technology in complex formations [29]. However, problems such as incomplete data collection and transmission delay seriously affect the monitoring effect, so it is necessary to build a stable and real-time data link and intelligent decision system.

Data acquisition and transmission: In complex formations, data acquisition and transmission face many challenges, such as signal attenuation and interference. In order to ensure the integrity and real-time of data, it is necessary to adopt more stable and efficient data acquisition and transmission technology. For example, optical fiber sensing technology can be used for data acquisition and data transmission through optical fiber networks to ensure real-time and stability of data.

Intelligent monitoring system: Intelligent monitoring system is an important means to achieve full dynamic monitoring. Through the introduction of AI and ML technology(see Fig. 7), intelligent monitoring of the drilling process can be achieved. For example, based on real-time monitoring data, AI systems can predict possible problems during drilling and automatically adjust drilling parameters to ensure a smooth drilling process.

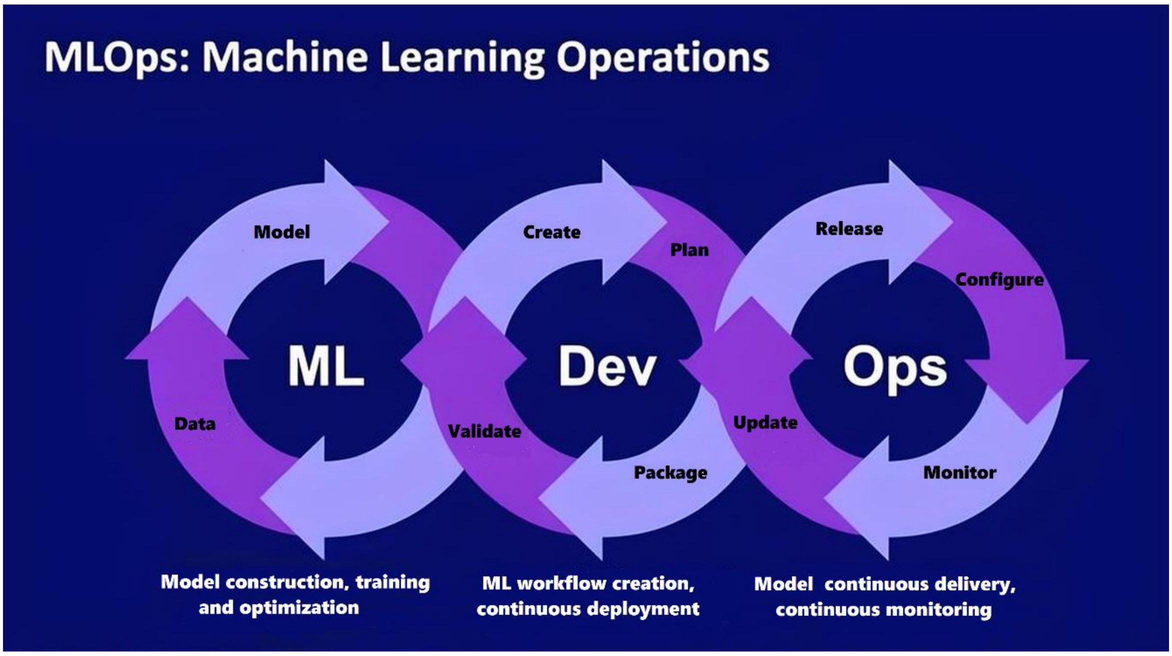

Fig. 7 Machine Learning Operations (From the network)

Intelligent decision system: Intelligent decision system is an important means to achieve HDD technology intelligence [30]. With the introduction of AI and ML technologies, intelligent decisions can be made about the drilling process. For example, based on historical data and real-time monitoring data, the AI system can automatically generate the optimal drilling plan and adjust the plan in real time according to changes in the drilling process to ensure the smooth drilling process.

Under complex formation conditions, trenchless horizontal directional drilling technology faces some key problems, such as bit guidance and trajectory control, hole wall stability maintenance, data transmission and intelligent monitoring. Through optimized guidance systems, real-time monitoring technology, drilling fluid pressure control, drilling parameter optimization, data acquisition and transmission technology, intelligent monitoring systems and intelligent decision systems, these challenges can be effectively addressed to ensure the successful application of HDD technology in complex formations.

5. Conclusion

This paper systematically summarizes the research status of the key technologies of trenchless horizontal directional drilling equipment, and discusses the technology of guided drilling, hole wall stability analysis, equipment automation and intelligence, and green construction. Although China has made remarkable progress in horizontal directional drilling technology, there are still shortcomings in bit guidance and trajectory control, hole wall stability maintenance, data transmission and intelligent monitoring in complex formations. In the future, with the continuous maturity of new materials, intelligent control and information technology, trenchless horizontal directional drilling equipment will play a greater role in improving construction efficiency, ensuring project safety and achieving green construction, and providing more solid technical support for urban underground engineering construction.

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