Digitized Drilling-Rock Perception System Based on A Three-Stage Architecture

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Abstract. During the process of drilling, the drill bit makes direct contact with the engineering rock mass, and the feedback from the drill bit effectively represents the mechanical properties of the rock mass. Digital drilling technology allows for the real-time monitoring of key parameters such as rotational speed, torque, drilling pressure, and drilling velocity while drilling through rock formations. By delving into the geological data embedded within the responses of the drilling tools, a correlation between the feedback from the drilling tools and the essential engineering rock parameters can be established. Through the deployment of high-precision digital monitoring devices that automatically gather and analyze drilling data at various depths, a sophisticated Digitized Drilling Rock Perception (TSDDR) system with 1 insertion, 2 display, and 3 hidden structures is created, enabling the identification of both visible and concealed rock structures. The outcomes of this approach hold significant value in enriching the engineering drilling database, enhancing our comprehension of rock and soil characteristics, advancing engineering exploration techniques, and pinpointing potentially problematic geological features.

Keywords: digital drilling system; rock mass parameters; advanced drilling; geological drilling rig; engineering survey.

1 Introduction

In the past few decades, with the wave of economic construction, water conservancy and hydropower engineering has developed rapidly. At the same time, the theoretical and technical level of hydraulic and geotechnical engineering has also made significant progress [1-2]. The application in the field of geotechnical engineering requires more elemental and finer data, and monitoring instruments have random fluctuations in drilling data recorded by depth, which is difficult to identify and has a huge amount of data [3-4]. It is extremely difficult to establish a corresponding relationship between drilling data and actual formation depth [5]. To solve this problem, the application of time series monitoring technology to drilling data monitoring and the establishment of

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an automatic monitoring system for surface features of rotary impact drilling have become a new idea for technological innovation [6-7].

In recent years, artificial intelligence [8], communication technology [9], the Internet of Things [10], big data [11], and deep learning [12] technologies have developed rapidly, gradually solving the key software and hardware bottleneck problems of dativization and informatization. Each of these technologies has evolved rapidly, addressing and overcoming significant challenges related to the processing, analysis, and management of vast amounts of data - issues that were once considered major bottlenecks in achieving digital drilling.

Drawing on the intelligent perception technology applied to rock mass parameters in digital drilling engineering, known as "digital drilling technology," a new type of drilling system has emerged that seamlessly integrates software and hardware systems, theoretical methodologies, and data interpretation. The system, referred to as the Three-Stage Digital Drilling Rock Perception (TSDDR), represents a significant advancement over traditional drilling techniques. It incorporates an array of high-precision data collection instruments designed to capture critical parameters such as torque, speed, and pressure throughout the drilling process. Beyond mere data collection, the TSDDR system is equipped with sophisticated data mining and interpretation software that automatically establishes correlations between machine operations and rock characteristics. This innovative approach enables the creation of detailed mappings that articulate the interaction between the drilling machinery and the rock material. Another key feature of the TSDDR system is its utilization of data visualization techniques. This functionality not only facilitates real-time monitoring and analysis but also enhances the understanding of the rock mass condition for on-site personnel. The integration of these advanced technologies into the TSDDR system marks a step forward in drilling operations, offering a more informed, precise, and effective method for navigating through various rock formations.

2 Summary of the existing work

Digital drilling technology utilizes high-precision digital monitoring instruments to automatically collect and analyze drilling data that varies with depth. This technology allows for the comprehensive, continuous, and accurate acquisition of real-time information such as propulsion pressure, rotation speed, drilling torque, and voltage and current during rock drilling operations. By leveraging a wealth of data gathered throughout the drilling process, key indicators like drilling specific energy, drilling speed, and drilling power consumption can be calculated based on principles of mechanical equilibrium and energy conservation.

Through thorough analysis of the vast geological information embedded in drilling tool response data, a mapping relationship between drilling tool responses and engineering rock mass parameters can be established. This enables the analysis and measurement of strength parameters and spatial distribution characteristics of rock mass structures. The data can be visualized in 3D through software programs, providing crucial insights for stratigraphic interface recognition and classification of surrounding rock formations.

Digital drilling rig technology is not limited to conventional geological drilling but is also well-suited for advanced tunnel boring machine (TBM) drilling in tunnel engineering projects. It can assess the quality of rock mass ahead of the tunnel face and capture rock mass parameters through rock drilling trolleys used in drilling and blasting operations. This technology has been successfully implemented in major water conservancy and hydropower projects such as the Guangxi Datongxia Water Control Project, Yunnan Dehou Reservoir, Jilin Songhua Diversion Project, Lawa Hydropower Station, Xinjiang Nuer Reservoir, and Xizang Ali Reservoir.

3 Method and structure

The TSDDR system incorporates an array of high-precision instruments specifically designed for data acquisition, targeting essential drilling parameters such as torque, speed, and pressure throughout the entire drilling operation. Beyond mere data collection, the TSDDR system is enhanced with sophisticated data mining and interpretation software. This suite includes data preprocessing programs, theoretical analysis and derivations, and machine learning modeling, enabling it to autonomously identify relationships between the operations of the machinery and the characteristics of the rock. According to diverse engineering needs, the architecture of the TSDDR system is primarily structured into six layers, as follows:

Data port: Primarily utilized for data input, conversion, output, and integration with other software or platforms.

Hidden layer 1: Establishes the correlation between the digital drilling machine and rock perception. Parameters of the model are refined and set based on test results. Subsequently, data interpolation is implemented to facilitate drawing services.

Hidden layer 2: Incorporates built-in software for data cleaning, organization, filtering, and processing, ensuring data standardization, sorting data by time series and depth series, and meeting display requirements.

Hidden layer 3: Encompasses digital drilling data, engineering parameters, drilling identification, drilling positioning information, and the corresponding rock physical and mechanical parameter database.

Display layer 1: Involves system function buttons, exhibition of drilling rig response parameters, and graphical representation of data variations with depth or time.

Display layer 2: Presents one-dimensional, two-dimensional, and three-dimensional cloud maps of rock physical and mechanical parameters, primarily encompassing rock compressive strength, elastic modulus, rock hardness, tensile strength, integrity distribution, and brittleness.

4 Hardware system

Digital drilling technology incorporates high-precision digital monitoring instruments to automatically gather and analyze drilling data that varies with depth. This enables the comprehensive, continuous, and accurate acquisition of real-time response information such as propulsion pressure, rotation speed, drilling torque, and voltage and current during rock drilling. The hardware system primarily comprises data acquisition and processing devices, power devices, and high-precision digital sensors.

To cater to various types of drilling rigs, the hardware system typically necessitates secondary development and customization capabilities based on engineering requirements. It is equipped with multiple interfaces to facilitate flexible connections with large-scale mechanical equipment like engineering geological drilling rigs, TBM advanced drilling, and rock drilling rigs.

The hardware system of digital drilling technology offers adaptable configurability, allowing for the configuration of different application modules based on distinct engineering characteristics. This ensures the system's suitability and portability, promoting its widespread applicability.

5 Software system

A software system encompasses a compilation of programs and accompanying databases, which include a comprehensive data processing program for drilling response, a data analysis program for drilling process information, a deep learning analysis program for mapping the connection between drilling and rock parameters, and a database containing typical drilling tool response characteristics and rock physical and mechanical parameters. The software system operates in a process-oriented and intelligent manner, spanning from data collection to the generation of essential information.

By recording and analyzing the correlation between drilling information and the quality of the rock mass, this software system facilitates a foundation for expedited evaluation of rock mass quality without necessitating an increase in exploration workload.

5.1 Data preprocessing program

The primary objective of a data processing program is to transform the extensive and complex drilling response information into standardized data files that are organized, concise, and consistent. Initially, during the early stages of data processing, the main focus is on the time series axis, transitioning to the displacement series axis in the later stages. Both time series and displacement series complement each other in the processing workflow. Following file merging, essential operations such as effective drilling data extraction, outlier elimination, missing value interpolation, and noise filtering are conducted.

Subsequently, a standardized Digital Drilling Automatic Processing (DDAP) program is developed to generate a primary drilling parameter change chart based on sequences of time and displacement. Calculus processing is applied to the time curve of drilling depth data to discern the relationship between drilling response parameters and time (or displacement). This analysis captures variations in metrics like advance pressure, rotation speed, drilling speed, and drilling process index with depth (refer to Fig.1).

Drawing upon digital drilling data, the program determines the corresponding rock engineering mechanical properties (including integrity, uniaxial compressive strength, abrasion index, tensile strength, hardness, etc.) for various evaluation indicators (e.g., drilling speed, drilling process index, unit volume drilling energy consumption, cutting depth slope, etc.). Subsequently, the software visually represents the variations of drilling rock parameters with depth for comprehensive analysis.

The machine rock perception mapping relationship is the theoretical core of digital drilling technology. Based on the machine rock perception mapping relationship, data interpretation can be achieved, which not only meets the analysis of drilling data in conventional geological drilling, but also dynamically obtains engineering indicators such as rock quality, rock compressive strength, and wear resistance. This improves the intelligence level of drilling and has important engineering application value.

By delving into the variation patterns of propulsion pressure, drill pipe speed, and drilling speed, a mapping relationship between various related factors is established (refer to Fig.2).

Based on this, a new indicator, namely the Drilling Process Index (DPI), which can be used to quantitatively evaluate the integrity of rock mass is proposed, as shown in Eq. (1). Normally, the DPI value of a complete rock mass is 0-2, the DPI value of a block rock mass is 2-3, and the DPI value of a fractured rock mass is greater than 3.

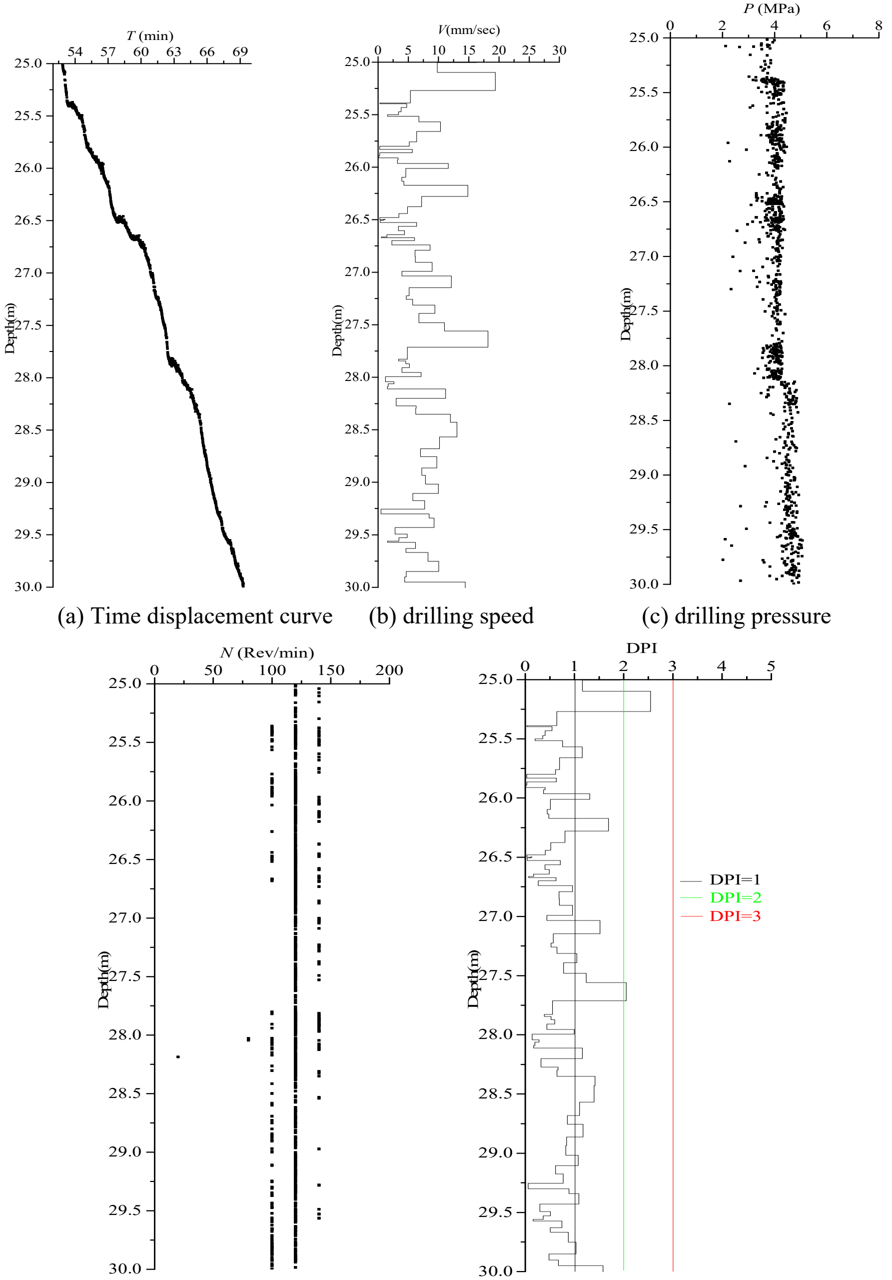
$$DPI = \alpha \cdot V \cdot F^{-0.5} \cdot N^{-0.5} \tag{1}$$

In equation (1): α is a constant parameter related to the drill bit specifications; V is the drilling speed; F is the propulsion pressure; N is the rotational speed.

5.2 Data display program

One of the fundamental objectives of digital drilling technology is to provide an assessment of the mechanical properties of engineering rock masses through the perception relationship between machines and rocks. In practical applications, engineers require intuitive displays of rock mass parameters, thus necessitating the development of data display programs.

To address this need, a three-dimensional imaging software for rock engineering characteristics is developed based on the correlation between the response characteristics of digital drilling tools and substantial rock parameter data. For instance, by taking the rock mass quality index RQD as an example, the 3D imaging software can not only illustrate the variation of two-dimensional drilling rock mass parameters with depth but also generate a porous 3D model after interpolation, as depicted in Fig.3.



(a) Time displacement curve (b) drilling speed (c) drilling pressure

(d) rotational speed (e)DPI

Fig. 1. Processing and display of the DDAP program implemented through python language

Machine rock perception mapping relationship

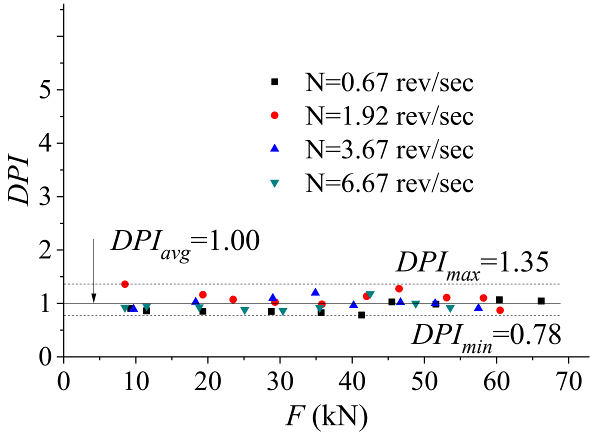


Fig. 2. Drilling response parameter change law curve

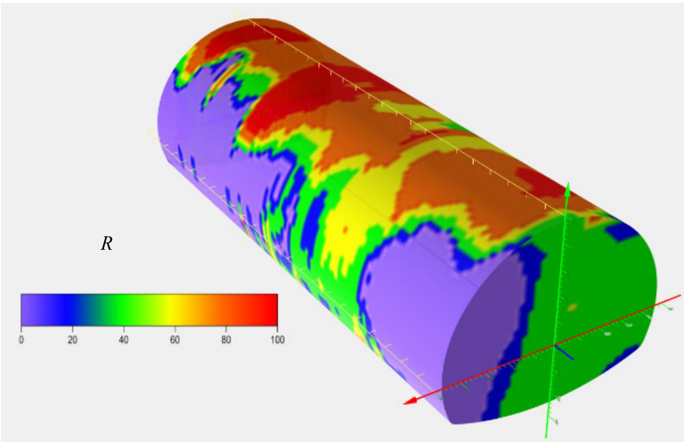


Fig. 3. Schematic diagram of the three-dimensional display of lithology of digital drilling formation.

In summary, digital drilling technology enables the digitalization and visualization of drilling tool response characteristics and rock mechanics parameters. The development of two-dimensional and three-dimensional imaging software for rock engineering characteristics allows real-time updates of drilling rock parameters with depth and time. Moreover, it enables spatial interpolation of drilling group information, thereby generating comprehensive rock physical and mechanical parameters such as rock quality indicators, hardness, uniaxial compressive strength, and brittleness. The 3D cloud map display function facilitates the visualization of geological formations in any cross-section or specific area, providing valuable visual guidance for engineering purposes.

6 Conclusion

Digital drilling technology and the TSDDR system represent significant advancements in the field of geological exploration and rock mass quality assessment. These technologies integrate hardware systems, data analysis software, and foundational databases to leverage big data analysis and cloud technology for comprehensive understanding and evaluation of drilling information and rock mass characteristic parameters. This integration allows for a rapid, cost-effective alternative to traditional labor-intensive and resource-heavy exploration methods, facilitating quicker project progression.

(1) Innovative Aspects:

1. Integration of Big Data and Cloud Technology: The use of big data analysis and cloud technology for comprehending drilling information and acquiring rock mass characteristic parameters is a revolutionary approach that enhances efficiency and accuracy in rock mass quality assessment.

2. Advanced Data Processing Software: The development of data processing software with a human-machine interaction module that includes functions like data cleaning, noise reduction, data connection, and extensive drilling data calculation represents a significant technological advancement. This software also supports 3D data rendering and spatial display, offering a more intuitive understanding of the rock mass.

3. Rapid Evaluation without Additional Workload: The ability to quickly evaluate the quality of engineering rock masses without increasing the exploration workload is a game-changer. It reduces the time and resources required for traditional exploration and evaluation methods.

4. Intelligent Perception of Rock Properties: The TSDDR system's potential in providing theoretical backing for advancing drilling industry practices and its application in the intelligent perception of rock physical and mechanical properties are innovative aspects that could revolutionize the field.

(2) Limitations and Suggestions for Further Study:

Despite the promising aspects of digital drilling technology and the TSDDR system, there are limitations that need to be addressed through further research:

1. Data Quality and Integrity: Ensuring the quality and integrity of the data collected through digital drilling technology is critical. Future studies should focus on developing more robust data validation and verification processes to minimize errors and improve the reliability of the assessments.

2. Adaptability to Diverse Geological Conditions: The current system may not fully account for the vast diversity in geological conditions encountered across different sites. Research should aim at enhancing the adaptability and versatility of the technology to cater to a broader range of geological environments.

By addressing these limitations and exploring the suggested areas for further study, the potential of digital drilling technology and the TSDDR system can be fully realized, leading to more efficient, accurate, and sustainable practices in the field of geological exploration and rock mass quality assessment.

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