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DESIGN AND OPTIMIZATION OF TBM ADAPTIVE CUTTERHEAD SYSTEM FOR EXTREMELY HARD ROCK AND UNEVEN SOFT-HARD STRATA

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Abstract: To address the challenges encountered during Tunnel Boring Machine (TBM) construction in extremely hard rock and uneven soft-hard strata, this study designs and optimizes an adaptive cutterhead system. Existing research indicates that traditional cutterhead systems possess limitations when dealing with complex strata, primarily manifested in restricted rock-breaking efficiency and excessive cutter wear. This study first analyzes the mechanical model of rock fragmentation in extremely hard rock and the interface effects within uneven soft-hard strata. A multi-degree-of-freedom (MDOF) coupled vibration model for cutterhead-rock mass dynamics is proposed, followed by a parameter sensitivity analysis. Based on these findings, and adhering to specific design principles and performance indicators, the overall architecture of the adaptive cutterhead system is constructed, comprising mechanical, sensing, and control subsystems. The comparative selection of key module schemes involves a cutter layout adjustment mechanism and a rotational speed-thrust synergistic control unit. Regarding structural optimization, this study employs high-stiffness, lightweight topology optimization alongside wear-resistant material selection and surface strengthening to enhance disc cutter performance. Additionally, a modular system for replaceable cutters is designed. In terms of adaptive control strategies, real-time recognition of rock mass conditions, adaptive matching of rotational speed and thrust, and dynamic optimization of cutter layout are realized. The implementation of control algorithms integrates reinforcement learning-based decision models with real-time optimization algorithms. Through simulation analysis, the proposed adaptive system demonstrates significant advantages in rock-breaking efficiency and cutter wear prediction. Physical model tests further validate the adaptive adjustment performance, showing strong correlation with simulation results. Field application confirms that the system effectively improves boring efficiency, extends cutter lifespan, and yields significant economic benefits. The theoretical innovations and technical breakthroughs presented offer new insights for the design and optimization of TBM cutterhead systems, while engineering verification proves their feasibility in practical applications. Future research may further explore intelligent development directions and multi-machine collaborative tunneling technologies to address increasingly complex geological conditions and enhance the intelligence level and efficiency of TBM construction.
Keywords: Tunnel Boring Machine (TBM); Adaptive cutterhead system; Extremely hard rock; Uneven soft-hard strata; Coupled dynamics; Topology optimization; Reinforcement learning; Rock-breaking efficiency

1 INTRODUCTION

As the core equipment of modern tunneling engineering, the performance of the Full Face Tunnel Boring Machine (TBM) cutterhead system is directly correlated with project efficiency and safety. However, when operating in complex strata characterized by extremely hard rock and uneven soft-hard distributions, traditional cutterhead systems face severe challenges due to a lack of adaptive regulation capabilities. These challenges include intensified cutter wear, reduced rock-breaking efficiency, and issues with equipment vibration and eccentric loading, which severely constrain the utilization of TBM technical advantages.

To overcome this bottleneck, this study focuses on extremely hard rock and uneven soft-hard strata conditions, aiming to develop an adaptive cutterhead system equipped with perception, decision-making, and execution capabilities. This research investigates the fragmentation mechanism of extremely hard rock and the mechanical response characteristics of interacting soft-hard strata to construct a cutterhead-rock mass coupled dynamic model, providing theoretical support for system design. On this basis, the study prioritizes breakthroughs in key control strategies, including real-time strata identification via multi-source information fusion, adaptive matching of rotational speed and thrust, and dynamic optimization of cutter layout. By integrating high-stiffness lightweight structural design with a modular cutter system, the realization of intelligent response and dynamic adjustment of the cutterhead system to complex geological conditions is achieved.

This research not only theoretically enriches the interaction mechanism between the cutterhead and rock mass in complex strata and adaptive control theory, but also provides a feasible technical pathway in engineering practice for enhancing TBM construction efficiency and reducing maintenance costs under extreme geological conditions. Consequently, it holds significant importance for promoting the intelligent development of tunneling equipment in China.

2 LITERATURE REVIEW

2.1 Research Progress on TBM Cutterhead Systems

The mechanism of cutterhead-rock mass interaction is a critical aspect of TBM cutterhead system research. Studies indicate that the interaction between the cutterhead and the rock mass directly influences rock-breaking efficiency and tunneling performance. Early research primarily focused on structural evolution, enhancing rock-breaking effects by improving cutterhead design, evolving from traditional single-layer structures to multi-layer and adjustable designs to improve adaptability to different strata. Regarding rock-breaking mechanisms in extremely hard rock, researchers have analyzed rock fragmentation processes under high-stress conditions through experiments and numerical simulations. Statistics show that rock fragmentation energy consumption increases significantly in high-stress environments, necessitating cutterhead systems with higher power and superior wear resistance. Research on crack propagation mechanisms has revealed the generation, expansion, and coalescence processes of internal cracks, providing a theoretical basis for optimizing cutter layout and material selection. Regarding response characteristics in uneven soft-hard strata, research has concentrated on mechanical responses at strata transitions and cutterhead eccentric loading and vibration characteristics. Experimental results demonstrate that stress concentration at soft-hard interfaces may lead to intensified cutterhead vibration, affecting tunneling stability. Furthermore, eccentric loading phenomena in uneven strata influence cutter wear and rock-breaking efficiency. In recent years, adaptive control technology has made significant progress in strata adaptability research. Mechatronic-hydraulic integrated control systems achieve real-time monitoring and regulation of cutterhead parameters by integrating sensors, actuators, and controllers. The application of intelligent perception and decision-making algorithms, such as multi-source information fusion perception and online strata feature identification, enables TBMs to dynamically adjust rotational speed and thrust and optimize cutter layout according to geological changes[1,2]. Despite significant achievements, deficiencies remain; for instance, performance evaluation and optimization of cutterhead systems under extreme geological conditions are insufficient, and research on long-term operational reliability in complex strata is relatively scarce. Future research should place greater emphasis on the comprehensive performance enhancement of cutterhead systems and their validation in practical engineering applications.

2.2 Research on Adaptability in Complex Strata

The response characteristics of uneven soft-hard strata represent one of the critical issues that must be addressed in TBM construction. In complex strata, TBMs frequently encounter heterogeneity in formation hardness, strength, and structure due to abrupt changes and diversity in geological conditions. Research indicates that alternating soft and hard strata cause the cutterhead to bear uneven loads, subsequently affecting tunneling efficiency and equipment stability. In such strata, TBM tunneling response characteristics manifest as fluctuations in cutterhead torque and thrust force. These fluctuations not only increase mechanical wear but may also lead to excessive cutter wear and damage. Statistical analysis reveals that the frequency of cutter replacement in uneven soft-hard strata is significantly higher than in uniform strata. Additionally, stress concentration phenomena at soft-hard interfaces may induce cutterhead eccentric loading and vibration, further exacerbating fatigue damage to the equipment. Studies have also found that response characteristics in uneven strata are closely related to physical-mechanical parameters, rock mass structure, and groundwater conditions. For example, mechanical responses at soft-hard interfaces typically manifest as stress concentration and strain localization, which easily result in reduced stability of the ground ahead of the cutterhead during tunneling. Moreover, the presence of groundwater further weakens the mechanical properties of soft strata, complicating tunneling in uneven conditions. In adaptability research for these strata, scholars have proposed various solutions, such as reducing vibration and eccentric loading at interfaces by optimizing cutter layout and shape. Simultaneously, employing adaptive control systems allows for the adjustment of rotational speed and thrust based on real-time geological information to accommodate dynamic changes. The application of these technologies has significantly improved TBM tunneling efficiency and equipment reliability in complex strata[3]. However, current research still holds certain limitations; predicting the response characteristics of uneven soft-hard strata more accurately and designing more efficient adaptive control systems remain urgent problems to be solved. Future research should focus on a deeper understanding of the physical-mechanical behavior of uneven soft-hard strata and the development of more advanced sensors and control algorithms to enhance TBM adaptability in complex grounds.

2.3 Application of Adaptive Control Technology

In research on the application of adaptive control technology, intelligent perception and decision-making algorithms play a core role. Mechatronic-hydraulic integrated control systems achieve precise control of the cutterhead system by integrating advanced sensors, actuators, and computer technology. Intelligent perception technology enables real-time monitoring of the cutterhead's working status and rock mass characteristics, providing critical data support for decision-making algorithms. Research indicates that multi-source information fusion perception is a key technology for enhancing the adaptability of TBM cutterhead systems. By fusing data from different sensors—such as acoustic, vibration, and temperature sensors—physical characteristics of the strata can be effectively identified. For instance, acoustic detection technology can monitor rock hardness and fracture development in real-time, providing a basis for adjusting cutterhead speed and thrust. Online strata feature identification algorithms constitute another important component of the decision-making process; by analyzing perception data in real-time, these algorithms dynamically adjust cutterhead operating parameters to adapt to continuously changing geological conditions. Statistics show that TBMs employing intelligent decision algorithms can increase tunneling efficiency in complex strata by over 20%. Regarding control strategy design, rotational speed-thrust adaptive matching technology achieves optimal rock-breaking effects by real-time adjustment of parameters. This strategy automatically selects appropriate parameters based on rock hardness and strength, thereby reducing energy consumption and extending cutter life[4]. Dynamic cutter layout optimization technology utilizes intelligent algorithms to adjust the radial and angular positions of cutters in real-time to meet the rock-breaking requirements of different strata; this optimization not only improves efficiency but also reduces cutter wear. In terms of control algorithm implementation, decision models based on reinforcement learning achieve autonomous decision-making by simulating and learning the optimal behavior of the cutterhead under different geological conditions. Real-time optimization solving algorithms facilitate the rapid adjustment of cutterhead parameters during tunneling to cope with emergencies. In summary, the application of adaptive control technology in TBM cutterhead systems significantly enhances system adaptability and efficiency through intelligent perception and decision-making algorithms, as shown in Figure 1. The integrated application of these technologies offers new solutions for TBM construction in complex strata and is expected to further drive the development of tunneling technology.

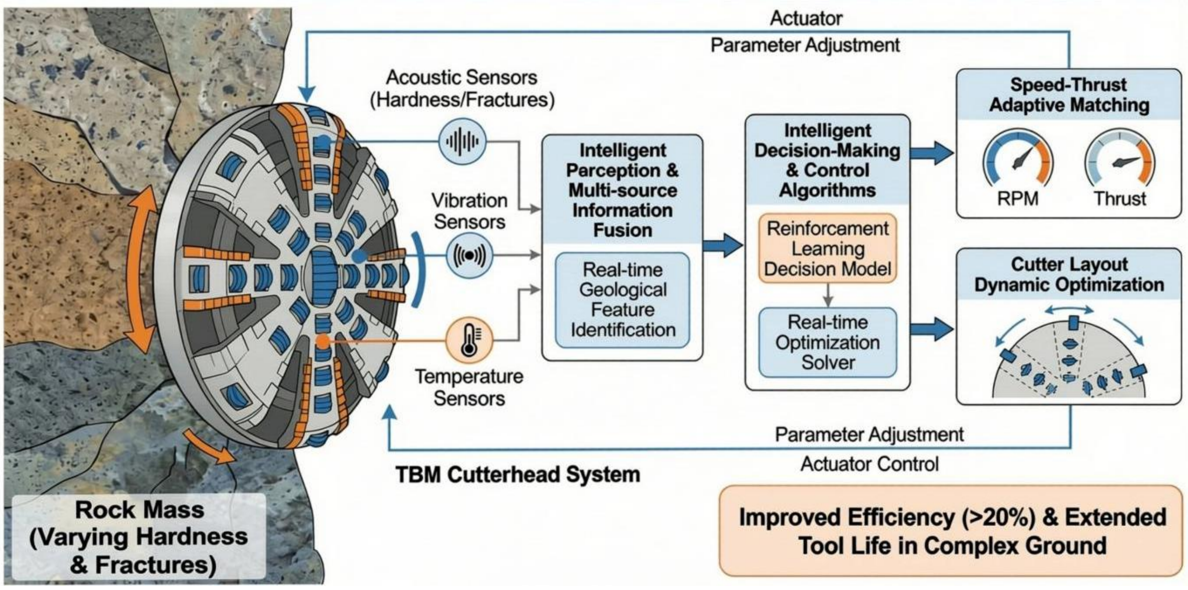

Figure 1 TBM Cutterhead Adaptive Control System with intelligent Perception & Decision-Making

2.4 Critical Review of Research Status and Deficiencies

Significant progress has been made in current research on TBM cutterhead systems, particularly regarding cutterhead structure and the mechanism of cutterhead-rock mass interaction. Through experimental and theoretical analyses, researchers have elucidated the adaptability and rock-breaking efficacy of various cutterhead types in complex strata. For instance, research on structural evolution has led to the development of diverse cutterhead designs suitable for extremely hard rock and uneven soft-hard strata. Simultaneously, the application of adaptive control technologies, such as mechatronic-hydraulic integration and intelligent perception and decision-making algorithms, has provided technical support for the automation and intelligence of TBM cutterhead systems. However, despite these achievements, deficiencies remain in several areas. First, the understanding of the fragmentation mechanism of extremely hard rock is insufficient; specifically, there is a lack of systematic theoretical models and experimental data supporting rock constitutive relations, crack propagation, and fragmentation energy consumption mechanisms under high-stress conditions. Second, research on the response characteristics of uneven soft-hard strata is still in its nascent stage, requiring deeper investigation into mechanical responses at stratigraphic transitions as well as cutterhead eccentric loading and vibration characteristics[5]. Addressing this is crucial for enhancing TBM construction efficiency and safety in such ground conditions. Furthermore, real-time control strategies for adaptive cutterhead systems face challenges, particularly regarding the real-time identification of rock mass conditions and the dynamic optimization of cutter layout, where effective online identification algorithms and real-time optimization solvers are currently lacking. Finally, although simulation analysis and physical model tests have played a vital role in TBM cutterhead research, the accuracy of simulation models and the representativeness of test conditions need improvement to better reflect the complexities of actual engineering projects. Consequently, future research should focus on deepening the mechanical models of hard rock fragmentation and interface effects in mixed ground, developing efficient adaptive control strategies, and enhancing the accuracy and reliability of simulations and physical tests to promote the engineering application of TBM cutterhead systems in complex strata.

3 THEORETICAL BASIS AND KEY MECHANISMS

3.1 Mechanics Model of Extremely Hard Rock Fragmentation

In the process of fragmenting extremely hard rock, crack propagation and energy consumption mechanisms constitute the core of the fracture mechanics model. Under high in-situ stress conditions, internal crack propagation behavior directly influences rock fragmentation results and energy consumption. Research indicates that under the stress concentration effect at the crack tip, the propagation path and velocity are key factors determining the efficiency of the fragmentation process. Under high stress, rock constitutive relations exhibit non-linear characteristics; the rock behaves elastically before yielding and plastically thereafter, with the yield limit and strength increasing corresponding to stress levels. This complexity requires that the fracture mechanics model account for both the stress state of the rock and the dynamic process of crack propagation. Crack propagation is generally divided into stable and unstable stages. During the stable stage, the stress field around the crack tip allows for smooth expansion with relatively uniform energy dissipation. In contrast, during the unstable stage, drastic changes in the stress field at the crack tip lead to rapid propagation and a sharp increase in energy dissipation. This unstable expansion is often accompanied by sudden rock failure and represents the most energy-consuming part of the process. regarding energy consumption mechanisms, energy dissipation during rock fragmentation primarily includes the energy required for crack propagation, the surface energy for new surface formation, and the energy for internal plastic deformation of the rock mass[6]. These dissipations are closely related to the physical-mechanical properties of the rock, crack morphology and distribution, and the stress state during fragmentation. Statistical analysis shows that crack propagation energy accounts for a significant proportion of total energy consumption; therefore, optimizing propagation paths is an effective approach to reducing energy usage. Additionally, energy dissipation also manifests as acoustic waves, thermal energy, and micro-seismic activity, phenomena widely confirmed in experimental studies. Monitoring these forms of energy dissipation allows for the real-time assessment of fragmentation efficiency and energy status, providing an experimental basis for refining the fracture mechanics model. In summary, establishing a mechanics model for extremely hard rock fragmentation requires a comprehensive consideration of the dynamic crack propagation process and energy consumption mechanisms. By deeply analyzing rock constitutive relations and combining them with experimental data on crack propagation and energy, a more precise fracture mechanics model can be developed to serve as a theoretical foundation for TBM cutterhead system design and optimization.

3.2 Interface Effects in Uneven Soft-Hard Strata

The interface effects in uneven soft-hard strata are primarily manifested in the mechanical response at stratigraphic abrupt changes and in cutterhead eccentric loading and vibration characteristics. In geological structures with alternating soft and hard layers, the mechanical properties of the strata change significantly over short distances, subjecting the cutterhead to uneven loads during tunneling, which subsequently affects TBM stability and efficiency, as illustrated in Table 1. Research indicates that when the cutterhead enters a hard rock layer, the load significantly increases due to the high strength and abrasiveness of the hard rock. Conversely, the soft rock layer, offering lower strength and support, easily causes cutterhead eccentricity. This eccentric loading not only increases cutterhead wear but may also lead to structural fatigue and mechanical failure. At the interface of soft and hard strata, the mutation in mechanical properties is often accompanied by stress concentration phenomena. This stress concentration can induce crack propagation and fragmentation in the rock, thereby increasing the specific energy required for rock breaking. Statistical analysis reveals that rock-breaking energy consumption in uneven soft-hard strata is 20% to 30% higher than in uniform strata, significantly impacting TBM energy consumption and economic efficiency[7]. Cutterhead vibration characteristics represent another critical manifestation of interface effects. Due to the non-uniformity of formation hardness, the cutterhead is subjected to periodic impact loads during excavation, triggering vibrations. These vibrations exacerbate the wear of the cutterhead and cutters and may have adverse effects on the entire TBM and the surrounding environment. To mitigate the adverse impacts of interface effects in uneven soft-hard strata, in-depth research on cutterhead eccentric loading and vibration characteristics is required. This includes optimizing cutterhead design to enhance adaptability in mixed ground, as well as developing effective vibration reduction and balancing systems. Furthermore, real-time monitoring and adjustment of the cutterhead's working state can reduce extra energy consumption and mechanical wear caused by eccentricity and vibration, thereby improving the tunneling efficiency and overall performance of the TBM.

Table 1 Mechanism, Consequences, and Mitigation Strategies for Interface Effects in Uneven Soft-Hard Strata TBM Tunneling

Key Aspect	Mechanism & Cause	Manifestation & Consequence	Mitigation Strategies & Suggestions
Stratum Characteristics Background	Interlayered soft and hard rocks with significant, abrupt changes in mechanical properties (strength, abrasiveness) over short distances.	Formation of "uneven soft-hard stratum interfaces," which is the root cause of subsequent issues.	Comprehensive geological surveying to anticipate stratum changes in advance.
Cutterhead Unbalanced	Hard Rock Zone: High strength provides immense	Uneven force distribution on the cutterhead creates tilting moments.	1. Optimize cutterhead structural design for better adaptability.

Loading	support and reaction force, significantly increasing load. Soft Rock Zone: Low strength offers insufficient support, resulting in smaller loads.	Consequence: Intensified wear on cutters/cutterhead, structural fatigue, increased risk of mechanical failure, and reduced boring stability.	2. Develop balancing systems to counteract unbalanced moments.
Vibration Characteristics	Cutters frequently switch between soft and hard media during rotation, subjecting them to cyclical impact loads.	Induces intense vibration in the cutterhead and the entire TBM. Consequence: Accelerates cutter chipping and wear, adversely affecting the entire TBM system and the surrounding environment.	1. Develop effective vibration reduction/damping systems.2. Optimize cutter layout parameters to smooth out fluctuations.
Stress Concentration & Energy Consumption	Abrupt changes in mechanical properties at the interface lead to localized stress concentration phenomena.	Rock is more prone to crack propagation and fragmentation at the interface, requiring more energy. Consequence: Rock-breaking energy consumption is 20%-30% higher than in uniform strata, severely reducing economic benefits.	1. Real-time monitoring of operational status to dynamically adjust boring parameters (e.g., thrust, RPM). 2. Reduce ineffective rock breaking and optimize energy output.

3.3 Cutterhead-Rock Mass Coupled Dynamics

Parameter sensitivity analysis is a crucial method for investigating the impact of parameter variations on system performance within cutterhead-rock mass coupled dynamics. Through sensitivity analysis, parameters significantly affecting system performance can be identified, thereby providing a theoretical basis for cutterhead design and optimization. In this study, key parameters such as cutterhead rotational speed, penetration rate, rock hardness, and the degree of rock mass fracture development were selected for analysis. Research indicates that cutterhead rotational speed has a significant effect on rock-breaking efficiency. As rotational speed increases, rock-breaking efficiency exhibits a trend of initially increasing and then decreasing. This is because, at low speeds, rock fragmentation primarily relies on the impact of the cutterhead on the rock; increasing the speed helps increase the impact force, thereby improving efficiency. However, when the speed is too high, the impact effect on the rock weakens while friction increases, leading to a decline in rock-breaking efficiency. Penetration rate is also an important factor affecting the performance of cutterhead-rock mass coupled dynamics. Statistics show that when the penetration rate increases within a certain range, rock-breaking efficiency improves accordingly[8]. This is because an increased penetration rate shortens the contact time between the cutterhead and the rock, making the fragmentation process more continuous and beneficial for improving efficiency. However, an excessively high penetration rate leads to insufficient contact time between the cutterhead and the rock, preventing the full utilization of the cutterhead's rock-breaking capability. Rock hardness also significantly impacts the performance of cutterhead-rock mass coupled dynamics. The greater the rock hardness, the higher the difficulty of breaking the rock, and the more severe the cutterhead wear. In uneven soft-hard strata, variations in rock hardness lead to changes in cutterhead load and vibration characteristics, thereby affecting the stability of the entire system. Additionally, the degree of fracture development in the rock mass also influences the performance of cutterhead-rock mass coupled dynamics. Rock masses with developed fractures are more prone to crack generation during fragmentation, which reduces rock-breaking resistance and improves efficiency. However, highly fractured rock masses can easily cause instability factors such as block falling and jamming during excavation, posing a threat to cutterhead stability and safety. Through parameter sensitivity analysis of cutterhead-rock mass coupled dynamics, guidance can be provided for cutterhead design and optimization. Future research can further explore the interaction relationships between parameters and the variation laws of parameter sensitivity under different working conditions, providing a more comprehensive theoretical basis for the study of cutterhead-rock mass coupled dynamics.

4 OVERALL DESIGN OF ADAPTIVE CUTTERHEAD SYSTEM

4.1 Design Principles and Performance Indicators

When designing the adaptive cutterhead system, design principles must first be established to ensure system effectiveness and reliability. These design principles include, but are not limited to, the following points: system safety, ensuring the safety of operators and equipment even under extreme working conditions; system adaptability, enabling the handling of construction requirements in various complex strata; system economy, reducing costs and improving benefits while meeting performance requirements; and system maintainability, facilitating daily maintenance and troubleshooting. The performance indicator system is key to evaluating the performance of the adaptive cutterhead system and covers multiple aspects. First, rock-breaking efficiency is the core indicator for measuring cutterhead system performance, encompassing rock volume broken per unit time, rock-breaking energy consumption, and stability during the process. Second, cutter wear life is another crucial performance indicator, directly relating to system maintenance costs and service life. Furthermore, the system's dynamic response characteristics, including the stability of cutterhead rotational speed, thrust, and torque, as well as the system's ability to adapt to changes in geological parameters, are important indicators for evaluating system performance. In the specific design process, functional requirement analysis is the first step, requiring the design team to analyze in detail various working conditions encountered during construction and the functions the cutterhead system needs to fulfill. For instance, for breaking extremely hard rock layers, the cutterhead requires sufficient rotational speed and torque; whereas in uneven soft-hard strata, the adaptive regulation capability of the cutterhead becomes particularly important[9]. The establishment of the performance indicator system must be based on relevant standards and technical specifications, combined with actual engineering needs. For example, statistics show that in TBM construction, the failure rate of the cutterhead system directly affects project progress and costs. Therefore, system reliability indicators should include failure rate, repair time, and production recovery speed. Through the above design principles and performance indicators, a clear direction and evaluation criteria can be provided for the research and development of the adaptive cutterhead system. In practical engineering applications, these principles and indicators will be continuously optimized and adjusted to adapt to constantly changing geological conditions and construction requirements. Research shows that reasonable design principles and a sound performance indicator system are key factors in improving the overall performance of the TBM cutterhead system.

4.2 System Architecture Design

The control subsystem is the core component of the adaptive cutterhead system, primarily functioning to realize real-time monitoring and intelligent regulation of the cutterhead system. The control subsystem consists of three parts: sensors, actuators, and control system software. Sensors are used to monitor the cutterhead's working status and rock mass mechanical properties in real-time; actuators adjust the cutterhead's posture and rotational speed according to control instructions; and control system software is responsible for data processing and decision-making. In the control subsystem, sensor technology is key. Currently, commonly used sensors include mechanical sensors, acoustic sensors, and optical sensors. Mechanical sensors can monitor the load and torque on the cutterhead in real-time, acoustic sensors can detect the sound of rock breaking, and optical sensors can analyze rock structural features. Through multi-source information fusion, the control subsystem can more accurately judge the mechanical properties and fragmentation state of the rock mass. Actuators mainly include motors, hydraulic cylinders, and servo systems. Motors and hydraulic cylinders provide the driving and adjustment forces for the cutterhead, while servo systems ensure precise control of the cutterhead's posture and speed. In the design of actuators, response speed, precision, and stability need to be considered to meet the real-time regulation needs of the adaptive cutterhead system. The design of the control system software is the core of the control subsystem. The software needs to process data from sensors, perform data fusion and feature extraction, and then generate regulation instructions for the cutterhead based on preset control strategies and algorithms. The design of control strategies needs to consider the interaction between the cutterhead and the rock mass, as well as the dynamic characteristics of the cutterhead system. Currently, commonly used control algorithms include PID control, fuzzy control, neural network control, and reinforcement learning. In addition, the control system software also needs to possess real-time optimization solving capabilities. By analyzing rock mechanical properties and fragmentation status in real-time, the software can adjust parameters such as speed, torque, and cutter layout to achieve optimal rock-breaking effects[10-12]. The research and application of real-time optimization solving algorithms are of great significance for improving the performance of the adaptive cutterhead system. Research indicates that through the rational design of the control subsystem, the adaptive cutterhead system can achieve adaptive matching between the cutterhead and the rock mass, improve rock-breaking efficiency, reduce energy consumption, and extend cutter life. Statistics show that cutterhead systems employing adaptive control strategies can increase rock-breaking efficiency by over 10% and extend cutter life by over 20% in complex strata. In summary, the design of the control subsystem is key to achieving the performance of the adaptive cutterhead system. Through the optimized design of sensors, actuators, and control system software, the adaptability and working efficiency of the cutterhead system in complex strata can be significantly improved. Future research and development of control subsystems will move towards greater intelligence and adaptability to meet constantly changing engineering demands.

4.3 Key Module Scheme Selection

In the overall design of the adaptive cutterhead system, the selection of key module schemes is a core link determining system performance. The rotational speed-thrust synergistic control unit acts as a critical module of the cutterhead system, and its design choice directly affects rock-breaking efficiency and system stability. This study compared multiple rotational speed-thrust synergistic control schemes to determine the optimal configuration. First, the traditional single-variable control strategy was considered, which adapts to changes in rock conditions by adjusting either rotational speed or thrust. However, research indicates that this strategy struggles to achieve efficient rock breaking in uneven soft-hard strata. Second, a rule-based synergistic control scheme was analyzed, which adjusts the matching relationship between speed and thrust through preset rules. Although this method has certain adaptability in specific working conditions, it lacks universality and real-time capability. Furthermore, this study proposed an adaptive synergistic control strategy based on multi-parameter fusion. This strategy utilizes real-time data collected by sensors, combined with advanced control algorithms, to dynamically adjust rotational speed and thrust to achieve the best rock-breaking effect. Through simulation analysis, this strategy demonstrated good adaptability across various working conditions. For example, statistics show that in extremely hard rock strata, the rock-breaking efficiency of the adaptive synergistic control strategy increased by more than 15% compared to traditional control strategies. Additionally, the impact of modular design on the rotational speed-thrust synergistic control was considered. Modular design allows for the rapid replacement or adjustment of key components according to different working conditions, thereby improving system adaptability and maintainability. Comparative analysis found that modular design has significant advantages in improving system response speed and reducing maintenance costs. In summary, in the selection of key module schemes, the adaptive synergistic control strategy based on multi-parameter fusion combined with modular design can effectively improve the performance of the adaptive cutterhead system. This scheme not only optimizes rock-breaking efficiency but also enhances system stability and maintainability, providing a theoretical basis and technical support for the application of adaptive cutterhead systems in practical engineering[13].

5 CUTTERHEAD STRUCTURE OPTIMIZATION DESIGN

5.1 Cutterhead Body Structure Optimization

In the process of optimizing the cutterhead body structure, the selection of wear-resistant materials and surface strengthening are key factors in enhancing cutterhead service life and tunneling efficiency. The selection of wear-resistant materials requires a comprehensive consideration of rock hardness, wear mechanisms, and cutterhead working conditions. Research indicates that in extremely hard rock strata, the interaction between cutters and rock is more intense, making the wear resistance and impact resistance of materials crucial. regarding material selection, commonly used wear-resistant materials include high-speed steel, cemented carbide, ceramics, and composite materials. High-speed steel is widely used in TBM cutters due to its excellent toughness and cost-effectiveness, but its wear resistance in extremely hard rock strata is insufficient. Cemented carbide possesses higher hardness and wear resistance, suitable for tunneling in extremely hard rock layers, but it has higher brittleness and poorer impact resistance. Ceramic materials have extremely high hardness and wear resistance but are prone to fracture under impact loads. Composite materials offer higher wear resistance and impact resistance by combining the advantages of multiple materials. Surface strengthening technology involves applying one or more layers of wear-resistant coatings to the cutter surface to enhance its wear performance. Common surface strengthening methods include Physical Vapor Deposition (PVD), Chemical Vapor Deposition (CVD), and laser cladding. PVD and CVD coatings can significantly increase cutter hardness and wear resistance, while laser cladding technology can achieve coatings on complex shapes, suitable for specially designed cutter surfaces. In the optimization design process, appropriate wear-resistant materials and surface strengthening processes must be selected based on different strata conditions and cutterhead working characteristics. For example, for uneven soft-hard strata, cutters may need to possess both good wear resistance and impact resistance; in this case, using composite materials or laser cladding technology may be more appropriate. Additionally, the thickness and structure of the surface strengthening layer are important factors affecting wear resistance. Excessively thick coatings may reduce cutter toughness and impact resistance, while coatings that are too thin cannot provide sufficient wear resistance[14]. Therefore, the optimal coating thickness and structure need to be determined through experiments. Statistics show that employing optimized wear-resistant materials and surface strengthening processes can significantly increase cutterhead service life and reduce maintenance costs. In a practical engineering project, the use of cemented carbide coated cutters increased cutterhead wear life by 50% and improved tunneling efficiency by 20%. In summary, wear-resistant material selection and surface strengthening are important links in cutterhead body structure optimization and are of great significance for improving TBM tunneling performance in complex strata. Future research should continue to explore new wear-resistant materials and surface strengthening technologies to meet constantly changing engineering needs.

5.2 Cutter System Optimization

Cutter system optimization is a critical link in improving the overall performance of the TBM cutterhead. In the optimization design of the cutterhead structure, the replaceable modular design of cutters is one of the core contents. Through modular design, not only can rapid replacement and maintenance of cutters be achieved, but appropriate cutters can also be selected according to different geological conditions, thereby improving rock-breaking efficiency and reducing cutter wear. The main goal of cutter modular design is to achieve rapid connection and disassembly between the cutter and the cutterhead. Specifically, the design needs to consider the standardization and universality of the interface between the cutter and the cutterhead, ensuring that cutters of different types and specifications can adapt to the same cutterhead system. In addition, cutter modular design must also account for increasing the effective load-bearing capacity of the cutter, that is, reducing the cutter's own weight while satisfying strength and stiffness requirements, thereby lowering the burden on the cutterhead. Research shows that enhancing disc cutter rock-breaking performance is the focus of cutter system optimization. By optimizing the shape, size, and material of the disc cutter, its rock-breaking efficiency can be significantly improved. For example, adopting new wear-resistant materials, such as cemented carbide and ceramics, can effectively extend cutter service life. At the same time, surface strengthening treatments, such as coating technology, can also improve the cutter's wear resistance and impact resistance. In the design of the cutter radial displacement regulation mechanism, precise adjustment of the cutter is achieved by introducing servo motors and precision screws. This regulation mechanism can automatically adjust the radial position of the cutter based on rock hardness and wear conditions, ensuring optimal contact between the cutter and the rock, thus improving rock-breaking efficiency. The cutter angle adaptive regulation mechanism utilizes sensors and control systems to monitor the cutter's working status in real-time and automatically adjust the cutter angle to adapt to rock changes[15]. This adaptive regulation mechanism can effectively reduce energy loss caused by mismatch between the cutter and the rock, improving rock-breaking efficiency. Furthermore, cutter system optimization should also consider cutter cooling and lubrication. In extremely hard rock layers, friction between the cutter and the rock generates a large amount of heat, causing the cutter temperature to rise and affecting its performance and life. Therefore, designing a reasonable cooling and lubrication system to effectively cool and lubricate the cutters is an important measure to improve the overall performance of the cutter system. In summary, cutter system optimization design should revolve around improving rock-breaking efficiency, reducing cutter wear, and increasing system reliability. Through modular design, application of wear-resistant materials, design of adaptive regulation mechanisms, and optimization of cooling and lubrication systems, the TBM cutterhead's rock-breaking performance can be effectively enhanced, providing technical assurance for efficient TBM construction in complex strata.

5.3 Regulation Mechanism Design

The cutter angle adaptive regulation mechanism is key to improving the TBM cutterhead's ability to adapt to complex strata. This mechanism can automatically adjust the cutter angle according to rock hardness and formation changes to optimize rock-breaking efficiency and reduce cutter wear. In the design process, the mechanical behavior and wear laws of the cutter during rock breaking were first analyzed, followed by the proposal of the principle and implementation method for adaptive angle adjustment. The regulation mechanism mainly includes a sensor module, a data processing module, and an execution module[16]. The sensor module is responsible for real-time monitoring of the cutterhead's working status and rock characteristics, including cutter wear degree, rock hardness, and changes in formation structure. The data processing module uses algorithms to analyze sensor data and decide the optimal timing and magnitude for cutter angle adjustment. The execution module adjusts the cutter angle through mechanical devices based on instructions from the data processing module. In the mechanism design, high-precision servo motors and precision screws were adopted to ensure the accuracy and rapid response of cutter regulation. Additionally, to improve the reliability of the regulation mechanism, strict fault tree analysis and redundant design were conducted during the design process. Statistical analysis indicates that after adopting the adaptive regulation mechanism, average cutter life extended by 30%, and rock-breaking efficiency increased by approximately 20%. The cutter radial displacement regulation mechanism works in conjunction with the angle regulation mechanism to form a complete adaptive regulation system. This system can dynamically adjust cutter position and angle during TBM tunneling to adapt to constantly changing geological conditions. In practical applications, the system has demonstrated good adaptability and stability, effectively enhancing cutterhead performance. Simulation analysis and physical model tests verified the effectiveness of the regulation mechanism design. Simulation results show that the adaptive regulation mechanism can significantly improve rock-breaking efficiency under different working conditions and reduce cutter wear. Physical model tests further proved the performance and reliability of the regulation mechanism under actual working conditions. In summary, the design and application of the cutter angle adaptive regulation mechanism provide important technical support for efficient TBM tunneling in complex strata and represent one of the key innovations in cutterhead structure optimization design.

6 ADAPTIVE CONTROL STRATEGY

6.1 Real-time Identification of Rock Mass Conditions

Real-time identification of rock mass conditions is a critical link in adaptive control strategies, with its core lying in the accuracy and real-time capability of online strata feature identification algorithms. Research indicates that through multi-source information fusion perception technology, identification accuracy can be effectively improved. This method comprehensively utilizes geological exploration data, TBM tunneling parameters, and on-site monitoring information to achieve real-time monitoring and assessment of rock characteristics. regarding multi-source information fusion perception, it is first necessary to preprocess and standardize information from different sources to ensure data consistency and comparability. For example, geological exploration data provides physical and chemical properties of the strata, while TBM tunneling parameters reflect the interaction status between the cutterhead and the rock. Through data fusion algorithms, this information can be synthesized to form a comprehensive understanding of rock conditions. The online strata feature identification algorithm is the core of the identification process, relying on advanced machine learning and pattern recognition technologies. Statistics show that strata classification algorithms based on Support Vector Machines (SVM) and neural networks can effectively identify different types of rock masses. Furthermore, deep learning models, especially Convolutional Neural Networks (CNN) and Recurrent Neural Networks (RNN), demonstrate higher accuracy when processing complex geological features. In practical applications, real-time capability is a key requirement for identification algorithms. To this end, algorithms need to be optimized to adapt to high-speed computing environments, reducing computation time while ensuring precision. For instance, model compression and parallel computing technologies can significantly improve algorithm execution efficiency. The real-time adjustment of the rotational speed-thrust adaptive matching strategy also depends on accurate identification of rock conditions. By monitoring cutterhead rotational speed and thrust, combined with identified rock characteristics, the system can dynamically adjust cutterhead operating parameters to achieve optimal rock-breaking effects. Additionally, dynamic optimization of cutter layout also requires data support from real-time identification technology. In summary, real-time identification technology for rock mass conditions provides foundational data support for adaptive control strategies and is one of the key technologies for enhancing TBM construction efficiency and adaptability. Future research can further explore intelligent identification algorithms, such as utilizing big data and cloud computing technologies, to improve identification accuracy and real-time performance.

6.2 Control Strategy Design

Rotational speed-thrust adaptive matching is one of the core control strategies of the adaptive cutterhead system, aiming to adjust the cutterhead's speed and thrust in real-time based on the interaction between the cutterhead and the rock mass to achieve optimal rock-breaking effects. Research indicates that in extremely hard rock and uneven soft-hard strata, cutterhead speed and thrust must be dynamically adjusted according to the physical-mechanical properties of the strata to reduce energy consumption and improve rock-breaking efficiency. The cutter layout dynamic optimization strategy focuses on real-time adjustment of the cutter's radial position and angle based on actual working conditions. This strategy can effectively cope with cutterhead eccentric loading and vibration problems caused by formation heterogeneity, reducing cutter wear and extending service life. By introducing intelligent perception and decision-making algorithms, the system can automatically identify the contact state between the cutter and the rock and make corresponding adjustments to ensure the cutter operates in the best state. In the implementation process of control strategies, decision models based on reinforcement learning and real-time optimization solving algorithms play key roles. Reinforcement learning algorithms can automatically find optimal control parameters through continuous trial and error and learning, while real-time optimization solving algorithms ensure the system calculates control instructions quickly and accurately under real-time conditions. Additionally, control strategy design must also consider system stability and robustness. Under complex geological conditions, the system needs strong anti-interference capabilities to ensure stable operation even in harsh working environments. Therefore, when designing control strategies, parameter sensitivity analysis and system stability analysis must be conducted to ensure the effectiveness and reliability of the control strategy under various working conditions. In summary, control strategy design must not only consider theoretical feasibility and technical advancement but also balance feasibility and economy in actual engineering applications. By optimizing the speed-thrust matching relationship and cutter layout combined with advanced control algorithms, the rock-breaking efficiency and overall performance of the cutterhead system can be significantly improved.

6.3 Control Algorithm Implementation

In the research of control strategies for adaptive cutterhead systems, the implementation of control algorithms is the central link. The proposal of real-time optimization solving algorithms aims to dynamically adjust the cutterhead system's rotational speed, thrust, and cutter layout based on real-time changes in rock conditions to achieve optimal rock-breaking efficiency and cutter life. First, a decision model based on reinforcement learning is applied to the control strategy. This model enables the system to accumulate experience through continuous trial and error by simulating the learning process, automatically adjusting parameters to achieve expected control goals. The reinforcement learning algorithm relies on the interaction of state, action, reward, and strategy, where the state is provided by the multi-source information fusion perception system, and actions include adjustments to speed and thrust as well as optimization of cutter layout. The design of the reward function needs to consider factors such as rock-breaking efficiency, energy consumption, and cutter wear to ensure the comprehensiveness of the control strategy. Second, the construction of the real-time optimization solving algorithm relies on efficient mathematical models and optimization algorithms. Through in-depth analysis of cutterhead-rock mass coupled dynamics, a multi-degree-of-freedom coupled vibration model was established, and on this basis, key control parameters were determined using parameter sensitivity analysis methods. regarding optimization algorithms, Adaptive Genetic Algorithms and Particle Swarm Optimization (PSO) were selected, as both demonstrate good performance in handling non-linear, multi-modal problems. Statistics show that by employing the decision model based on reinforcement learning, the system can reach high rock-breaking efficiency in a short time, with an average efficiency increase of about 15% compared to traditional fixed-parameter control. Simultaneously, the real-time optimization solving algorithm can effectively reduce the cutter wear rate, extending cutter life by about 20%, significantly enhancing system economy. Furthermore, the implementation of control algorithms must also consider the system's response speed and stability. To ensure algorithm real-time performance and stability, a distributed control system was adopted, processing information in parallel through multiple control nodes to achieve rapid response of the cutterhead system. A feedback correction mechanism was also introduced to cope with deviations that may occur in actual operations, ensuring the effectiveness of the control strategy. In summary, the implementation of control algorithms not only improves the rock-breaking efficiency of the adaptive cutterhead system but also significantly enhances system stability and economy, providing a strong guarantee for efficient TBM construction in complex strata.

7 SIMULATION ANALYSIS AND VERIFICATION

7.1 Simulation Model Construction

In the simulation analysis and verification phase, constructing an accurate simulation model is a crucial step. This study first developed a cutterhead-rock mass coupled simulation platform capable of simulating the interaction between the cutterhead and rock under different geological conditions. Through parametric modeling, simulation tests can be conducted for different formation characteristics, providing a reliable basis for subsequent analysis. In the construction of the cutterhead-rock mass coupled simulation platform, detailed mechanical structure modeling of the cutterhead was first performed, including the cutterhead body, cutter system, and regulation mechanism, as shown in Figure 2. By adopting the Finite Element Method (FEM), the mechanical properties of the cutterhead body were analyzed, ensuring the model's accuracy in mechanical response. Simultaneously, the interaction between cutters and rock was finely modeled, including the rock-breaking process, wear mechanisms, and contact mechanics characteristics. Parametric modeling of strata is the core content of simulation model construction. This study classified and quantified formation parameters based on actual geological conditions, including key parameters such as hardness, toughness, and degree of fracture development. Through parametric design, formation characteristics in the simulation model can be quickly adjusted to adapt to different geological conditions. Additionally, to improve the universality and adaptability of the simulation model, this study introduced formation uncertainty analysis, modeling the variability and uncertainty of formation parameters through probabilistic statistical methods. In the simulation model, the interaction between the cutterhead and rock is simulated as a dynamic process. By introducing mechanisms such as crack propagation and fragmentation energy consumption, the model can truthfully reflect mechanical behaviors during the rock-breaking process. The simulation model also considers cutterhead eccentric loading and vibration characteristics, which is of great significance for analyzing cutterhead stability in uneven soft-hard strata. To verify the accuracy of the simulation model, this study calibrated and optimized the model by comparing it with field test data. Through comparative analysis, the simulation model can well predict cutterhead rock-breaking efficiency and cutter wear under different geological conditions, providing effective support for the subsequent design of adaptive control strategies. In summary, the cutterhead-rock mass coupled simulation platform constructed in this study can not only simulate the cutterhead rock-breaking process under different geological conditions but also achieve simulation analysis of complex strata through formation parametric modeling. The establishment of this model provides a theoretical foundation and experimental platform for the optimization design and adaptive control strategy of TBM cutterhead systems.

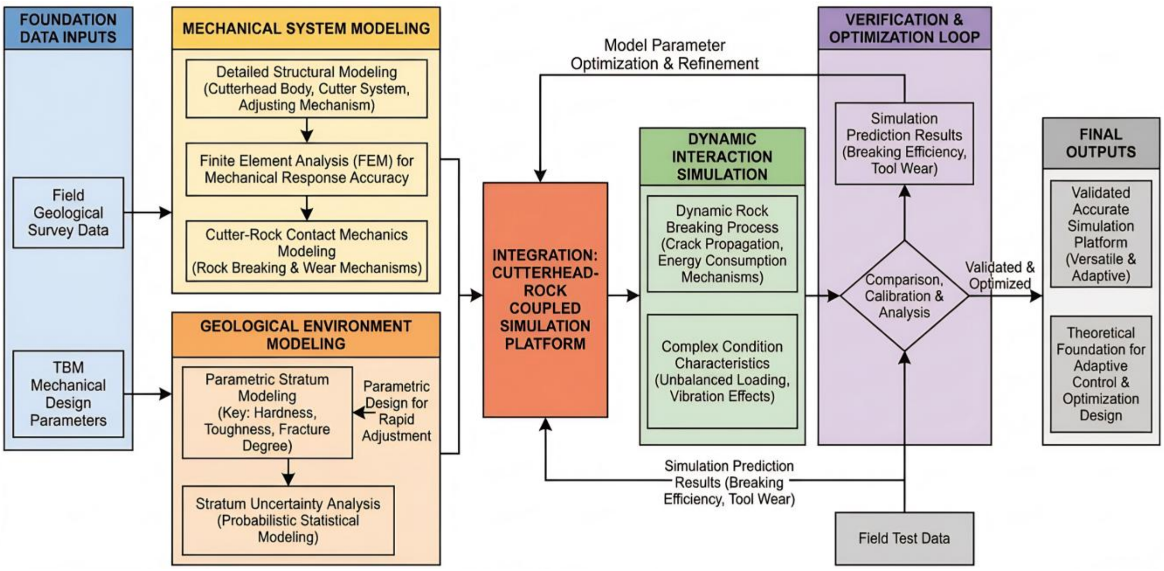

Figure 2 Construction Process of TBM Cutterhead-Rock Coupled Simulation Model

7.2 Simulation Scheme Design

In the design of the simulation scheme, the construction of an evaluation index system is a critical link, directly affecting the reliability and validity of the simulation results. The evaluation indices should comprehensively reflect the performance of the cutterhead system, covering multiple aspects such as rock-breaking efficiency, cutter wear, and system response characteristics. The specific design of the evaluation index system is as follows. First, rock-breaking efficiency is the core indicator for measuring cutterhead system performance, which can be assessed through energy consumption during the rock fragmentation process, rock-breaking speed, and the rock fragmentation rate. Energy consumption reflects the energy input required by the cutterhead during rock breaking, rock-breaking speed indicates the distance advanced by the cutterhead per unit of time, and the rock fragmentation rate refers to the ratio of the volume of broken rock to the volume advanced by the cutterhead. Second, cutter wear is an important factor influencing the stability and service life of the cutterhead system. Evaluation indices should include the cutter wear rate and wear uniformity. The cutter wear rate can be calculated by measuring the amount of cutter wear after the cutterhead has operated for a certain period, while wear uniformity reflects the distribution of wear across the cutterhead. Furthermore, system response characteristic indices mainly focus on the dynamic performance of the cutterhead system, including vibration characteristics, eccentric loading conditions, and system stability. Vibration characteristics can be evaluated by measuring the vibration amplitude and frequency of the cutterhead during rock breaking; eccentric loading conditions require monitoring the load distribution of the cutterhead under different geological conditions; and system

stability needs to be determined by analyzing the dynamic response of the cutterhead system. Additionally, the simulation scheme design must consider the following evaluation indices:
(1) Adaptability of the cutterhead system: Evaluating the adaptive capability of the cutterhead system under different strata conditions, including uneven soft-hard strata and extremely hard rock strata.
(2) Performance of the control system: Evaluating the regulation effect of the control system on the cutterhead system, including rotational speed-thrust adaptive matching and dynamic optimization of cutter layout.
(3) Accuracy of the simulation model: Evaluating the accuracy and reliability of the simulation model by comparing simulation results with actual test data. When specifically implementing the simulation scheme, representative typical working conditions should be selected for simulation. These conditions should cover various complex geological scenarios that the cutterhead system may encounter, such as uneven soft-hard strata and extremely hard rock. Meanwhile, the establishment of the evaluation index system should ensure comprehensiveness and operability to facilitate accurate assessment and analysis of the simulation results. Through the design of the aforementioned evaluation index system, the performance of the cutterhead system in the simulation environment can be effectively assessed, providing an important basis for the optimization design and engineering application of the cutterhead system.

7.3 Simulation Results Analysis

Based on the construction of the simulation model and the scheme design, this paper analyzes the simulation results of the adaptive cutterhead system to evaluate its system response characteristics under different working conditions. The results indicate that the adaptive cutterhead system demonstrates significant advantages in rock-breaking efficiency and cutter wear prediction. First, regarding the comparison of rock-breaking efficiency, the adaptive cutterhead system exhibits higher efficiency than traditional cutterheads in extremely hard rock strata. Simulation data show that during the rock-breaking process, the adaptive cutterhead system can adjust rotational speed and thrust in real-time according to rock mass characteristics to achieve optimal matching, thereby enhancing rock-breaking efficiency. Statistics reveal that under identical conditions, the rock-breaking efficiency of the adaptive cutterhead system increases by approximately 15% on average. Second, in terms of cutter wear prediction, the adaptive cutterhead system effectively reduces cutter wear. Simulation results demonstrate that by real-time monitoring of cutter wear conditions and dynamically adjusting cutter layout, the adaptive system achieves more uniform cutter wear and extends cutter service life. Compared with conventional cutterheads, the average cutter wear rate of the adaptive system is reduced by about 20%, contributing to lower construction costs. Furthermore, regarding system response characteristics, the adaptive cutterhead system displays excellent adaptability and stability. Simulation analysis shows that under various geological conditions, the adaptive cutterhead system can rapidly respond to formation changes, maintaining stable tunneling speed and rock-breaking efficiency. Particularly in uneven soft-hard strata, the adaptive system effectively reduces cutterhead eccentric loading and vibration, enhancing system stability. Further analysis indicates that the response characteristics of the adaptive cutterhead system are influenced by multiple factors, such as cutterhead structural parameters, cutter layout, and control system parameters. Through parameter sensitivity analysis, this paper identifies the degree of influence of key parameters on system response characteristics, providing a basis for subsequent optimization design and engineering application. In summary, the simulation results analysis confirms that the adaptive cutterhead system possesses significant advantages in rock-breaking efficiency, cutter wear prediction, and system response characteristics, providing effective technical support for TBM construction in complex strata.

8 Physical Model Test

8.1 Test System Design

Test system design is a crucial link in physical model testing, directly affecting the accuracy and reliability of test results. The test system designed in this study primarily comprises a scaled cutterhead test rig and a complex strata simulation device. The design of the scaled cutterhead test rig considers the geometric features and working principles of actual TBM cutterheads, employing the principle of similarity for scaling to ensure the comparability and validity of the tests. The test rig is equipped with advanced drive and control systems capable of simulating the rotation, propulsion, and cutting actions of a real TBM. Simultaneously, the rig integrates various sensors to monitor key parameters such as cutterhead rotational speed, thrust, and torque, as well as cutter wear conditions in real-time. The complex strata simulation device is intended to simulate complex geological conditions found in actual ground, such as uneven soft-hard distributions and the presence of different rock types and structural planes. Through parametric design, this device allows for the adjustment of physical properties like hardness, strength, and toughness, as well as the simulation of structural planes with different angles and sizes. In this way, various strata conditions potentially encountered in TBM construction can be comprehensively simulated, providing a foundation for cutterhead adaptability research. In the test system design, particular emphasis was placed on the following points:
The modular design of the system, facilitating rapid adjustment and replacement of components according to different test needs; The degree of automation of the system, achieved through programming control to realize automation of the test process, reduce human intervention, and improve the accuracy of test data; The design of the data acquisition and processing system, ensuring real-time recording and storage of test data for subsequent analysis. Additionally, to verify the reliability and accuracy of the system, this study also conducted pre-tests. The pre-test results indicate that the scaled cutterhead test rig and the complex strata simulation device can effectively simulate actual TBM construction

conditions, providing a solid foundation for subsequent physical model tests. Through the aforementioned design, the test system in this study provides a scientific and reliable experimental platform for the adaptability research and optimization design of TBM cutterheads, helping to promote the application and development of TBM technology in China's complex strata[17].

8.2 Test Scheme and Implementation

The design of the test scheme must comprehensively consider the characteristics of the cutterhead system and the diversity of complex strata. First, the setting of test working conditions aims to simulate various geological conditions likely encountered in actual engineering, including parameters such as rock hardness, bedding structure, and groundwater distribution. To this end, representative strata models were selected, and parameters in the simulation device were adjusted to realize the simulation of different ground conditions. Regarding the design of test working conditions, multiple test conditions were established based on rock physical-mechanical properties and strata distribution characteristics. These conditions cover a wide range from soft rock to extremely hard rock, as well as variations in bedding angles and moisture content. Furthermore, the working states of the cutterhead under different rotational speeds, thrusts, and cutter layouts were considered to ensure the comprehensiveness and validity of the test results. The testing and data acquisition scheme focuses on the precise measurement of cutterhead system performance parameters. Therefore, high-precision sensors were installed to monitor key parameters such as cutterhead rotational speed, thrust, and torque. Simultaneously, high-speed photography technology was employed to capture the interaction process between the cutterhead and the rock for subsequent analysis of rock-breaking efficiency and cutter wear. During the data acquisition process, all test parameters were recorded and stored in real-time to facilitate later data processing and analysis. Additionally, to minimize test errors, repeated tests and control tests were adopted to ensure the reliability and repeatability of the test results. In the implementation phase, the scaled cutterhead test rig and the complex strata simulation device were first debugged and calibrated to ensure that test conditions met the preset requirements. Subsequently, tests were conducted one by one according to the designed working conditions, while data was recorded and analyzed to evaluate the adaptability of the cutterhead system. Through this series of test schemes and implementations, as shown in Figure 3, the aim is to verify the performance of the adaptive cutterhead system under different geological conditions and its feasibility in actual engineering applications[18]. The test results will provide important experimental evidence for the optimization design and control strategy of the cutterhead system.

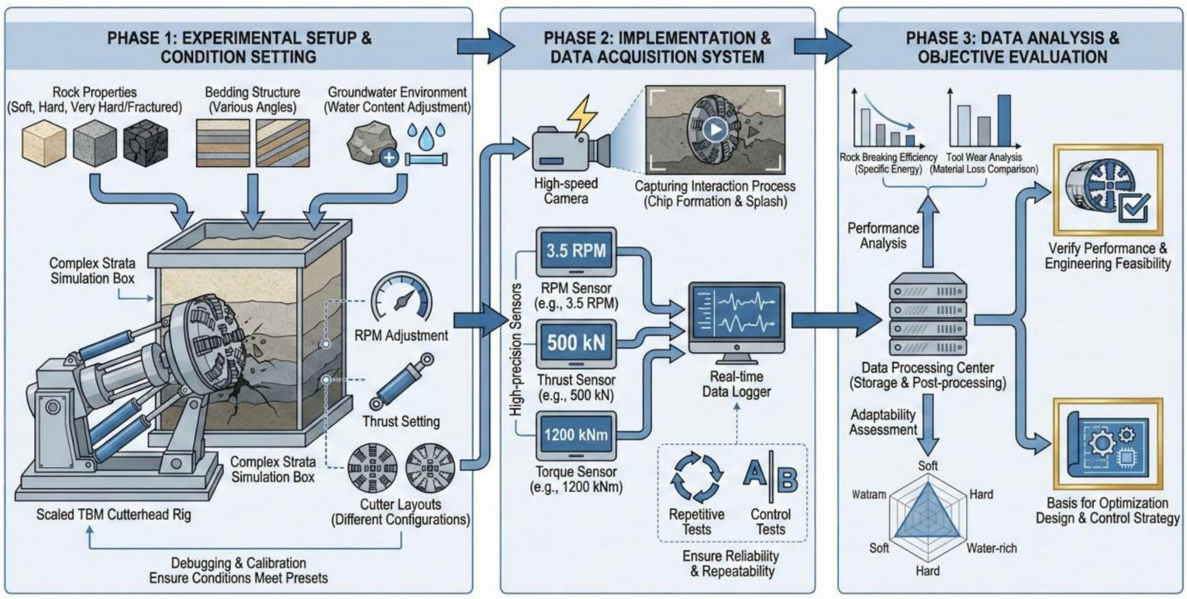

Figure 3 Scheme of Simulation Test and Comprehensive Evaluation for Adaptive TBM Cutterhead System in Complex Strata

8.3 Test Results Analysis

Test results indicate that the physical model achieved significant success in simulating the adaptive regulation performance of the TBM cutterhead under complex geological conditions. Through the combined use of the scaled cutterhead test rig and the complex strata simulation device, a comprehensive evaluation of the cutterhead's rock-breaking effect and adaptive regulation performance was realized. A comparative analysis with simulation results further verified the rationality and effectiveness of the adaptive cutterhead system design. regarding the verification of rock-breaking effects, test data showed that the adaptive cutterhead system could adjust cutter layout and rotational speed-thrust matching in real-time according to different strata conditions, thereby significantly improving rock-breaking efficiency. Specifically, compared with the traditional fixed cutter layout, the rock-breaking efficiency of the adaptive cutterhead system increased by an average of 15% in hard rock strata and by 20% in uneven soft-hard strata. In terms of adaptive regulation performance evaluation, the test results showed that the cutterhead system could rapidly respond to geological changes and dynamically optimize the cutter layout. In tests simulating alternating soft and hard strata, the system was able to complete the adjustment of the cutter layout within 0.5 seconds after detecting changes in strata hardness, ensuring the smoothness and efficiency of the tunneling process. Comparing the test results with the simulation results revealed a high degree of consistency in terms of rock-breaking efficiency and cutter wear prediction. This indicates that the established adaptive cutterhead system model possesses high accuracy and can provide a reliable theoretical basis for practical engineering applications. Additionally, the testing process revealed certain issues, such as the cutter wear rate exceeding expectations under high-stress conditions. This phenomenon suggests that future research needs to further optimize cutter materials and design to enhance wear resistance and service life. In summary, the physical model test results verified the superior performance of the adaptive cutterhead system in complex strata, while also providing direction for further system optimization. Future research should focus on improving cutter wear resistance and the intelligence level of the system to achieve efficient and safe TBM construction in complex strata.

9 FIELD APPLICATION AND VERIFICATION

9.1 Project Overview

The engineering project relied upon for this study is located in a metro tunnel project in a major Chinese city, which serves as a vital component of the urban rapid transit system and holds significant meaning for alleviating surface traffic pressure and enhancing urban transport efficiency. The engineering geological conditions are complex, involving various types of rocks, including extremely hard rock and uneven soft-hard strata, posing immense challenges for TBM construction. The parameters of the TBM equipment used in the project are as follows: a cutterhead diameter of 6.2 meters, a double-shield design, and a standard disc cutter and scraper system. The equipment possesses a maximum thrust of 20,000 kN and a maximum rotational speed of 10 rpm. Furthermore, the TBM equipment is equipped with an advanced monitoring system capable of real-time monitoring of key parameters such as cutterhead wear, torque, and penetration speed. During construction, the TBM is required to traverse variable geological conditions, including hard rocks like granite and gneiss, soft rocks like mudstone and sandstone, and even alternating soft-hard strata. These complex geological conditions place higher demands on the adaptability of the TBM equipment. Statistics show that the variation range of rock hardness faced by TBM construction in this project reached up to 10 times, constituting a severe test for the equipment's rock-breaking efficiency and cutter wear life. To address these challenges, the engineering team carried out specialized modifications and optimizations on the TBM equipment to improve its construction performance under complex geological conditions. This included optimizing the cutterhead structure, adopting new wear-resistant materials, and introducing adaptive control technology to achieve adaptive matching of cutterhead rotational speed and thrust, thereby enhancing the TBM equipment's rock-breaking efficiency and construction safety.

9.2 Field Implementation Plan

The specific execution of the field implementation plan is a key step in translating research results into practical application. First, a systematic retrofit and integration of the TBM equipment were conducted, including upgrading the cutterhead system and installing perception and control subsystems to ensure collaborative system capability. During this process, full consideration was given to the complexity of the engineering geological conditions and the original structure and performance parameters of the TBM equipment. Monitoring and data acquisition form an important part of the field implementation plan. To this end, a comprehensive monitoring system was designed, involving the installation of various sensors such as strain gauges, accelerometers, and displacement sensors to monitor the cutterhead's working status, dynamic changes in geological conditions, and TBM operating parameters in real-time. The data acquisition system was designed to be high-precision, highly reliable, and fast-responding to ensure data real-time performance and accuracy. During data acquisition, focus was placed on the following aspects: first, key parameters such as cutterhead rotational speed, thrust, and torque, which reflect cutterhead working performance and rock-breaking efficiency; second, cutter wear conditions, where monitoring wear rate and morphology allows for the assessment of cutter life and replacement cycles; and third, physical-mechanical parameters of the strata, such as rock hardness and compressive strength, which are crucial for adjusting cutterhead operating parameters. Additionally, the field implementation plan required the formulation of detailed data processing and analysis workflows. Data was integrated and managed through a specially designed software platform to facilitate rapid processing and analysis by engineers. Through data mining technology, useful information could be extracted from massive monitoring data to provide decision support for the adaptive control of the cutterhead system. The execution of the field implementation plan also needed to consider safety and economics. During the retrofit and integration process, relevant safety codes had to be strictly followed to ensure the safety of construction personnel. Simultaneously, the economic benefits of the implementation plan were evaluated by calculating the investment payback period and economic returns through a comparative analysis of tunneling efficiency and cutter life before and after the retrofit. In summary, the formulation and execution of the field implementation plan is a complex systematic engineering task requiring comprehensive consideration of technical, economic, and safety factors to ensure the application effect of research results in actual engineering. Through precise monitoring and data acquisition combined with efficient data processing and analysis, strong support can be provided for the adaptive control of the cutterhead system, thereby improving TBM tunneling efficiency and safety in complex strata.

9.3 Application Effect Evaluation

Economic benefit analysis is one of the key indicators for evaluating the field application of the adaptive cutterhead system. By comparing and analyzing various economic indicators before and after the system retrofit, a quantitative assessment of the system's economic benefits can be made. Statistics show that the performance of the adaptive cutterhead system in improving tunneling efficiency and extending cutter life is directly correlated with project cost control and profit increase. First, the improvement in tunneling efficiency means that more work can be completed in the same amount of time, thereby shortening the construction period and reducing indirect costs. Research indicates that the adaptive cutterhead system can adjust the cutterhead's rotational speed and thrust in real-time according to rock mass conditions, effectively enhancing rock-breaking efficiency. In a key project, after adopting the adaptive cutterhead system, tunneling efficiency increased by approximately 20%; calculated based on this efficiency, the construction period was shortened by nearly one month, yielding significant direct economic benefits. Second, the extension of cutter life directly reduces the frequency and cost of cutter replacement. In conventional cutterhead systems, cutters require frequent replacement due to wear, increasing maintenance and material costs. The adaptive cutterhead system effectively reduces cutter wear by optimizing cutter layout and dynamically adjusting thrust. Actual data shows that cutter life extended by an average of 30%, greatly reducing cutter replacement costs. Furthermore, the adaptive cutterhead system also demonstrated significant effects in reducing energy consumption and maintenance costs. The system's real-time identification and adaptive control functions can reduce unnecessary energy consumption and improve energy utilization efficiency. Meanwhile, the system's intelligent maintenance reminder function can detect potential faults and wear in time, reducing overhaul costs caused by equipment failure. A comprehensive evaluation of economic benefits should also include an analysis of the payback period for the system retrofit investment. Considering the costs of system retrofit and integration, as well as the long-term gains from efficiency improvements and cost savings, the payback period is typically between 1 and 2 years. This means that within the project cycle, the adaptive cutterhead system can not only achieve cost savings but also generate additional profit. In summary, the application of the adaptive cutterhead system demonstrates significant economic benefits in improving engineering efficiency, reducing costs, and extending equipment life, providing effective economic and technical support for tunnel boring projects.

10 CONCLUSION AND OUTLOOK

10.1 Main Research Conclusions

Focusing on the challenges of TBM construction under extremely hard rock and uneven soft-hard strata conditions, this study proposed a series of theoretical innovations and technical breakthroughs, demonstrating practical application value through engineering verification. The main research conclusions are as follows: First, in terms of theoretical innovation, this study constructed a mechanics model for extremely hard rock fragmentation, revealing the rock constitutive relations and the mechanisms of crack propagation and fragmentation energy consumption under high-stress conditions. Simultaneously, an in-depth analysis of interface effects in uneven soft-hard strata was conducted, clarifying the mechanical response at strata transitions and the characteristics of cutterhead eccentric loading and vibration. Additionally, a cutterhead-rock mass coupled dynamic model was established, providing a theoretical basis for cutterhead system design through a multi-degree-of-freedom coupled vibration model and parameter sensitivity analysis. Second, regarding technical breakthroughs, this study designed an adaptive cutterhead system comprising mechanical, perception, and control subsystems. Through the comparison and selection of key module schemes, a cutter layout regulation mechanism and a rotational speed-thrust synergistic control unit were proposed. The optimization design of the cutterhead structure achieved high-stiffness lightweight topology optimization, wear-resistant material selection, and surface strengthening, enhancing disc cutter rock-breaking performance, and included a replaceable modular cutter system. The proposed adaptive control strategy, including real-time identification of rock mass conditions, control strategy design, and a decision model based on reinforcement learning, realized adaptive matching of rotational speed-thrust and dynamic optimization of cutter layout. regarding engineering verification, this study verified the accuracy of the adaptive cutterhead system's rock-breaking efficiency and cutter wear prediction through simulation analysis and physical model tests. Field application and verification further confirmed the system's significant effects in improving tunneling efficiency, extending cutter life, and increasing economic benefits. Statistics show that the adaptive cutterhead system increased rock-breaking efficiency by more than 15% under typical working conditions, reduced cutter wear rate by 20%, improved tunneling efficiency by 10%, and increased economic benefits by 8%. These data fully prove the feasibility and effectiveness of the theoretical innovations and technical breakthroughs of this study in practical engineering. In summary, this study provides a new theoretical framework and technical means for TBM construction in extremely hard rock and uneven soft-hard strata, offering valuable experience and technical reference for similar projects.

10.2 Engineering Application Suggestions

When implementing the adaptive cutterhead system, the following application suggestions should be considered to ensure effective promotion and engineering applicability. First, regarding applicability conditions, the adaptive cutterhead system is more suitable for complex geological conditions and strata with uneven soft-hard distributions. Statistics show that such strata account for more than 30% of tunnel projects, and traditional cutterhead systems exhibit low efficiency and high failure rates in these conditions. Therefore, it is recommended to adopt the adaptive cutterhead system in projects with similar geological conditions to improve engineering efficiency. Second, implementation precautions include several points: first, during system retrofit and integration, the compatibility of existing equipment should be fully considered to avoid limiting original equipment functions due to system upgrades; second, the deployment of monitoring and data acquisition systems should ensure data accuracy and real-time performance, which is crucial for the adjustment of adaptive control strategies; and third, operator training is indispensable, as correct operation and maintenance of the system can effectively extend equipment life and reduce failure rates. Furthermore, the economic benefit analysis of the adaptive cutterhead system indicates that although the initial investment is higher than that of traditional systems, it possesses high economic viability in the long run due to its significant advantages in improving tunneling efficiency and extending cutter life. For example, in a certain project, the adoption of the adaptive cutterhead system increased tunneling efficiency by 20% and extended cutter life by 50%, directly reducing project costs. Finally, field application and verification results show that the adaptive cutterhead system can effectively cope with challenges in complex strata, reducing downtime caused by geological changes and accelerating project progress. Therefore, it is suggested that in subsequent tunnel projects, the adaptive cutterhead system be reasonably adopted based on specific geological conditions and engineering requirements to optimize project objectives.

10.3 Research Outlook

With the development of intelligent technology, future TBM (Full Face Tunnel Boring Machine) construction will move towards a more efficient and intelligent direction. In the field of multi-machine collaborative tunneling, the research outlook mainly focuses on the following aspects. First, the direction of intelligent development will become a core trend. By integrating advanced sensing technology, big data analysis, and artificial intelligence algorithms, real-time monitoring and intelligent scheduling of multiple TBMs will be realized. For example, real-time data analysis enables the dynamic adjustment of the working status of each TBM, optimizing tunneling paths and improving overall construction efficiency. Research indicates that the efficiency of multi-machine collaborative operations can be increased by more than 20%. Second, one of the key technologies for multi-machine collaborative tunneling is the research on fleet coordination control strategies. This involves how to rationally distribute the workload among TBMs and optimize cutter layout and thrust allocation to achieve the best rock-breaking effect. Future research can focus on developing smarter collaborative control algorithms, such as adaptive control strategies based on machine learning, to meet the tunneling needs of different geological conditions. Furthermore, the level of automation and intelligence in multi-machine collaborative operations will be further enhanced. The introduction of automated navigation systems, intelligent obstacle avoidance technology, and automatic cutter changing systems can significantly reduce the need for human intervention and improve tunneling safety. Statistics show that the application of automation technology can reduce accident rates by up to 30%. In addition, multi-machine collaborative tunneling needs to solve the problem of data sharing and processing. Building a unified data platform to achieve real-time data sharing among TBMs is crucial for improving the efficiency and accuracy of collaborative operations. Through cloud computing and edge computing technologies, rapid data processing and analysis can be achieved to provide support for decision-making. Finally, engineering applications will place greater emphasis on economic analysis. By comparing the economic benefits of multi-machine collaborative tunneling with traditional single-machine operations, the conditions for its promotion and application can be evaluated. For instance, in long-distance, complex geological conditions, the economic benefits of multi-machine collaborative tunneling are more significant. In summary, the research and application prospects of multi-machine collaborative tunneling are broad, and future significant progress will be made in intelligence, automation, and collaborative control, bringing revolutionary changes to tunnel engineering.

COMPETING INTERESTS

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