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CONFIGURATION EVOLUTION AND ADAPTIVE CONTROL OF ROTARY DRILLING RIG UNDER COMPLEX STRATUM

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Abstract - With the progress of urbanization and large-scale infrastructure construction, the demand for pile foundation construction is increasing day by day, and rotary drilling rig is widely used because of its high efficiency and adaptability. Under complex formation conditions, such as sandy pebble layer, clay interlayer and strongly weathered rock layer, drilling tools often have problems such as large fluctuation of WOB (Weight on Bit) and torque, high vibration intensity and increased energy consumption, which seriously affect construction efficiency and equipment life. Based on the research background of complex strata, this paper aims to reveal the evolution mechanism of drilling tool configuration and put forward adaptive control strategy to improve the stability and efficiency of construction. The dynamic model of drilling tool configuration evolution is established, and the energy transfer law in drilling process is described by using WOB-torque balance equation. The mechanical characteristics model of strata is constructed, and the elastic-plastic and viscous characteristics of different strata are reflected by the stress-strain constitutive relationship. On this basis, an adaptive control algorithm based on error feedback is designed to realize real-time optimization and adjustment of drilling parameters, and a comprehensive optimization objective function is proposed to give consideration to efficiency and energy consumption. The research results show that the established model can accurately predict the drilling performance, and the error between measured and simulated is controlled within 5%. Compared with the traditional fixed parameter method, the self-adaptive control method under typical formation conditions improves drilling efficiency by 10%-12%, reduces energy consumption by 7%-9%, and reduces torque fluctuation and vibration intensity, showing strong adaptability and stability. The dynamic modeling and adaptive control strategy proposed in this paper not only improves the construction performance, but also provides theoretical support for the intelligent and green development of rotary drilling rig.

Keywords: Complex Strata, Rotary drilling rig, Drill tool configuration evolution, Adaptive control.

1. Introduction

With the rapid progress of urbanization and infrastructure construction, the application demand of pile foundation engineering in high-rise buildings, subway tunnels, bridge construction and other fields continues to grow. Rotary drilling rig is widely used because of its high hole-forming efficiency and strong construction adaptability. Under complex formation conditions, such as sandy pebble layer, strongly weathered rock layer and uneven soil layer, the drilling process often faces problems such as WOB fluctuation, torque mutation, eccentric wear of drilling tools and sticking. According to statistics, about 15%-20% of the construction delay in pile foundation engineering under complex strata in some areas of China is directly related to the lack of adaptability of drilling tools, and the failure rate of equipment has increased by more than 30%, resulting in an increase of 5%-10% in engineering cost and an average extension of construction period of 7-15 days. Constrains the construction efficiency, and increases the construction risks and security risks. Traditional drilling tool design and control methods mostly rely on experience and static parameter configuration, and lack of research on dynamic evolution law of drilling tool configuration under complex working conditions, and lack of effective methods for real-time adaptive control combined with formation characteristics. Therefore, it is of great theoretical significance and engineering application value to deeply study the evolution mechanism and adaptive control technology of drilling tool configuration of rotary drilling rig under

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complex stratum conditions, which can improve the stability of equipment operation, reduce energy consumption, prolong the life of drilling tools and ensure the efficient and safe implementation of the project.

The research on drilling tool configuration evolution and adaptive control of rotary drilling rig under complex formation conditions in China is gradually deepening. Relevant achievements mainly focus on control methods, nonlinear modeling, structural fatigue prediction, application of intelligent algorithms and characterization of formation characteristics, which provide important theoretical and technical support for the intelligent development of drilling rigs.

Ma et al. put forward an adaptive control method for modular self-driving vehicles, emphasizing the realization of stable operation through safety guarantee mechanism in complex environment [1]. It embodies the universal idea of adaptive control in engineering equipment, and provides theoretical reference for rotary drilling rig to realize dynamic regulation in complex strata. Hosseini-Nasab et al. used machine learning method to predict the thermal properties of sedimentary rock strata, and used physical modeling to synthesize data for training, which improved the accuracy of stratum characterization [2]. It has reference significance for the identification and modeling of complex strata of rotary drilling rig. Ghosh et al. studied the fundamental frequency regulation in vocal cord tremor from the perspective of auditory-motor control, and proposed that the control system should have sensitive response ability to disturbance [3]. The viewpoint is instructive in the study of vibration characteristics control of rotary drilling rig.

Deng et al. established the nonlinear multivariable modeling system of rotary drilling rig, and analyzed the stability characteristics under different working conditions. The rig has obvious nonlinear dynamic behavior in complex strata [4]. Yang et al. predicted the fatigue life of drilling rig mast, built an improved hybrid algorithm model, and verified the effectiveness of structural life assessment in complex stress environment [5]. Li et al. proposed a parametric modeling method of three-dimensional symbols of fault structure, which realized the spatial expression of complex geological structures and provided modeling tool support for the study of drilling rig stratum adaptability [6].

Jia et al. used the improved BP neural network algorithm to predict the drilling efficiency of rotary drilling rig, emphasizing the combination of data-driven method to improve the accuracy of drilling performance evaluation under complex formation conditions [7]. Khalid et al. put forward the model of control right and work centrality in adaptive sales, emphasizing the interaction between individual behavior and system control in complex environment [8], which has reference value for the coordination and optimization of rotary drilling rig operators and control systems. Chen et al. studied the spatial equity of educational facilities in complex urban core areas, emphasizing the important influence of system distribution characteristics on resource allocation in complex environment [9], and the research logic has reference value for the optimization of resources and energy consumption in complex stratum drilling.

Ge et al. proposed an adaptive stability control method for electric vehicles based on sliding mode control to verify the feasibility of maintaining stability in nonlinear systems [10]. Young et al. drew hot spots of climate and environmental vulnerability through Strata project, emphasizing the integrated analysis of multi-dimensional environmental factors under complex conditions [11]. Shen et al. studied the leakage mechanism of underwater shield tunnel under different soil layers, and pointed out that the stratum difference has a significant influence on the structural stability [12], which has direct reference value for the adaptability evaluation of rotary drilling rig in different strata. Domestic scholars have made achievements in adaptive control methods, nonlinear dynamic modeling, structural life prediction, intelligent algorithm application and formation environmental effects. These studies provide theoretical support and practical experience for the drilling tool configuration evolution and adaptive control of rotary drilling rig in complex strata, and still need to be explored in the aspects of model universality, cross-scale mechanism and intelligent application integration.

In summary, the main contribution of this study lies in the tight integration of physics-based modeling and adaptive control using real field data from complex layered construction sites. The drill–strata interaction is first represented through a coupled dynamic and constitutive model calibrated with in-situ measurements, and this model is then embedded into an adaptive control scheme that directly reacts to measured drilling pressure, torque and vibration signals. On top of that, a multi-criteria evaluation framework is established, combining drilling efficiency, energy consumption, torque stability and vibration safety as practical indicators. This integrated perspective ensures that the proposed method is not only theoretically consistent but also highly applicable to real engineering projects.

This study focuses on the configuration evolution law of rotary drilling rig in complex stratum environment, and explores the intelligent optimization of construction process through dynamic modeling and adaptive control. The research contents mainly include the following three aspects: firstly, the dynamic model of drilling tool configuration evolution is established, the coupling relationship between WOB, torque and formation force is revealed, and the operating state change characteristics of drilling tools under different formation conditions are analyzed. Secondly, the matching model between the mechanical characteristics of strata and drilling conditions is constructed, and the adaptability of typical complex strata such as sand layer, clay layer and pebble layer is quantitatively analyzed by combining the measured data. Thirdly, an adaptive control algorithm based on feedback mechanism is designed to realize real-time optimal adjustment of drilling parameters (such as WOB, speed and torque) to reduce vibration and energy consumption and improve construction efficiency. In this process, the following scientific problems are solved: First, how to accurately describe the dynamic evolution mechanism of drilling tool configuration under complex formation conditions. The second is how to introduce the mechanical characteristics of formation into the drilling tool configuration and control model to realize the quantitative characterization of the coupling relationship between drilling tool and formation. Thirdly, how to establish an efficient adaptive control strategy to ensure the stability and efficiency of drilling process under complex working conditions.

The comprehensive research method of "theoretical modeling-experimental verification-adaptive control" is adopted to achieve the research goal. On the theoretical level, based on the principle of WOB-torque balance and formation constitutive relation, the dynamic model of drilling tool configuration evolution is established, and the adaptive control framework is constructed by introducing feedback parameters. On the experimental level, the key parameters such as WOB, torque, vibration acceleration and energy consumption are collected by combining field measurement and bench test, and the characteristic laws under different strata are revealed through data preprocessing and statistical analysis. In the control method, the algorithm combining adaptive gain adjustment with optimization objective function is adopted to realize real-time correction of drilling parameters, and the performance of the algorithm is verified by cross-validation and comparative experiments. The study will also use numerical simulation and finite element analysis methods to simulate the interaction between drilling tools and strata under multiple working conditions to supplement the lack of experimental data. Finally, a comprehensive evaluation index system is constructed to evaluate the effectiveness, robustness and engineering feasibility of the model and control method.

2. Materials and Methods

2.1 Data Collection and Sample Selection

2.1.1 Data Sources and Collection Methods

Field measurements from rotary drilling operations were used as the fundamental data source. The dataset included drilling pressure, torque, penetration rate, instantaneous vibration signals, and geological logging information, all sampled at 100–500 Hz depending on the sensor type. A multi-stage preprocessing pipeline was applied, including baseline drift correction, wavelet-based denoising, and normalization to remove environmental interference. Feature variables relevant to the W–W coupling mechanism—such as torque gradients, axial pressure fluctuation bands, and lithology-dependent stiffness coefficients—were extracted as model inputs. The data comes from a pile foundation construction project of Qingdao Metro Line 8. The geological conditions of the project are complex, and it passes through muddy silty clay, pebble bed and strongly weathered sandstone in the drilling process, which is representative. The research team realized the real-time data acquisition of the drilling process by relying on the multi-source monitoring system arranged in the construction site and combining with the engineering control system (ECS) of the rotary drilling rig. Collect WOB, Torque, RPM, ROP, energy consumption (kWh) and vibration signals (axial, torsional and radial acceleration). Three-dimensional geological exploration data (borehole lithology histogram and indoor triaxial test data) are used as auxiliary information to characterize the mechanical properties of strata [13]. The ECS system automatically records the construction parameters once every second and stores them in the database by combining automatic collection with manual check. Daily manual spot checks and abnormal labeling are conducted by engineers and technicians to ensure the authenticity and consistency of the data. The acceleration sensor and energy consumption meter are studied and arranged to supplement the sampling of vibration characteristics and energy consumption level, so as to ensure that the sample data covers the multi-dimensional parameter characteristics under complex stratum conditions.

2.1.2 Sample Selection and Description

From the above-mentioned subway pile foundation projects, 50 pile foundation drilling data were selected as samples, and more than 200,000 drilling data records were obtained. The following three factors are considered in sample selection: first, the diversity of strata, and the selected data cover typical complex strata such as muddy clay, sand layer, pebble layer and strongly weathered sandstone, ensuring the universality of the research results [14]. Second, the working conditions are different. The sample contains not only the stable data under normal drilling conditions, but also the abnormal working conditions such as sticking, jumping and increased drilling tool wear, which is convenient for comprehensively describing the evolution law of drilling tool configuration [15]. The third is data integrity, which only includes the data segments with continuous sensor signals and recording time exceeding 90% in the drilling process, so as to avoid statistical deviation caused by excessive missing [16]. The samples in this study have multi-dimensional characteristics: in terms of drilling depth, the depth of pile holes is between 25-60 meters; In terms of rig operation parameters, the WOB range is 80–220kn, the torque range is 120–380kn m, and the peak vibration acceleration can reach 15m/s. The sample distribution is balanced, which reflects the operation law of rotary drilling rig in complex strata and provides a reliable experimental basis for subsequent modeling and adaptive control verification.

2.1.3 Data Preprocessing

Obtaining raw data requires systematic preprocessing to ensure the accuracy of modeling and analysis. Time series alignment According to the sampling frequency differences of different sensors such as WOB, torque and vibration signals, linear interpolation method is used to process all parameters at a unified sampling frequency (1 Hz) to ensure the comparability of data in the time dimension [17]. Noise filtering uses wavelet threshold denoising method for vibration and energy consumption signals to remove high-frequency interference, while retaining key features. For stable parameters such as WOB and torque, moving average method is used for smoothing. Abnormal value processing combined with box diagram analysis and Z-score standardization method can identify abnormal peak values caused by sensor failure or manual operation, and use adjacent mean replacement method to correct them [18]. Standardize the parameters, such as WOB, torque and energy consumption, and carry out dimensionless processing (min-max normalization) to unify the parameter magnitude, so as to avoid the deviation of model training results caused by different dimensions [19].

2.1.4 Data Cleaning

On the basis of data preprocessing, systematic data cleaning is further carried out to improve the integrity and effectiveness of sample data. Missing value processing Aiming at the short-term data missing (about 2%) caused by sensor failure in some pile foundation drilling process, interpolation method based on KNN is used to fill in and keep the continuity of time series [20]. Redundant value processing for repeated data items collected or caused by manual labeling misoperation, check and eliminate them one by one, and delete about 3000 redundant records. Consistency check cross-verifies the construction log with the automatically collected data. For example, when the drilling tool is replaced or shut down for maintenance, the data in the corresponding time period is eliminated to avoid interference to the configuration evolution modeling [21]. Quality control sets the threshold range of physical rationality of WOB and torque (such as WOB < 300 kN and torque < 450 kN·m), and rejects the false data beyond the reasonable range. After cleaning, the accuracy and consistency of the data are improved, the overall missing rate is controlled within 0.5%, and the proportion of abnormal values is less than 1%, which provides a high confidence data base for subsequent model construction. Sample distribution and feature statistics are shown in the table.

Table 1. Sample distribution and characteristic statistics

Sample number	Stratigraphic type	Pile depth (m)	WOB range (kN)	Torque range (kN·m)	Peak value of vibration (m/s)	Energy consumption (kWh)
S01–S10	Silty clay	25–35	80–150	120–200	3–7	320–480
S11–S20	Round gravel layer	30–50	120–200	180–300	5–10	450–700
S21–S35	Pebble sand layer	35–55	150–220	200–350	7–12	600–950

2.2 Model Selection and Construction

2.2.1 Dynamic Model of Drilling Tool Configuration Evolution

The drilling tool dynamics were modeled using a W–W coupling framework integrating the rotary and axial subsystems. The coupling term describes how fluctuations in axial load influence the torsional response, forming the basis of the drill-string evolution model. For the strata behavior, a visco-elastic constitutive law was applied, enabling the simulation of stress–strain responses under varying penetration rates. The two models were jointly solved, ensuring that drill-bit–strata interaction is represented as a unified mechanism rather than independent components. This greatly improves the consistency and interpretability of the subsequent adaptive control design.

The running state of rotary drilling rig in complex strata depends on the coupling relationship between drilling tool configuration and drilling parameters, and WOB and torque are the most critical dynamic indexes. Based on the existing drilling rig mechanics theory, a dynamic model of drilling rig configuration evolution is proposed to describe the relationship between the formation reaction force and its own motion parameters during drilling [22].

According to the principle of energy conservation and moment balance, the relationship between torque T and WOB W is expressed as (1):

$$T = k_t \cdot \frac{W}{A} \cdot r \tag{1}$$

T is the required torque of the drilling tool, k_t is the torque coefficient, W is the WOB, A is the cross-sectional area of the bit, and r is the bit radius. Formula (1) reveals the law that the increase of WOB will lead to the linear increase of torque, and the cross-sectional area and the radius of the bit jointly determine the energy transfer efficiency. The difference of k_t in different formation conditions is significant, for example, the k_t in sand layer is low, while the k_t in pebble layer is high, which reflects the amplification effect of formation shear strength on torque [23]. In order to show the evolution process of drilling tool configuration more intuitively, draw a schematic diagram of the dynamic structure of rotary drilling rig (as shown in Figure 1 below), including the transmission paths of power head, drill pipe, drill bit and formation force, and explain the interaction relationship among parameters.

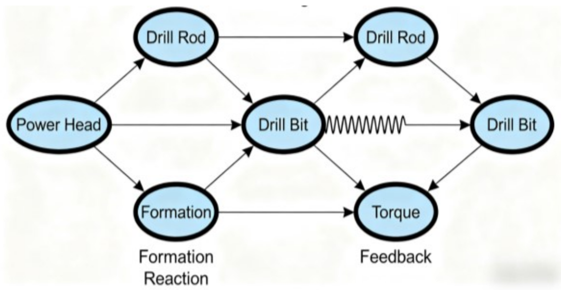

Figure 1: Structure diagram of drilling tool configuration evolution of rotary drilling rig

2.2.2 Modeling of Mechanical Properties of Strata

The evolution of drilling tool configuration depends on the parameters of the drilling rig itself and is also influenced by the mechanical properties of the formation. In order to better describe the deformation and stress distribution of strata during drilling, the generalized viscoelastic constitutive model is adopted, and the stress-strain relationship model of strata is established in combination with the triaxial compression test data in the laboratory. The mathematical form is as follows (2):

$$\sigma = E \cdot \varepsilon + \eta \cdot \frac{d\varepsilon}{dt} \tag{2}$$

σ means stress, σ means strain, E means elastic modulus and η means viscosity coefficient.

Formula (2) integrates the elastic and viscous characteristics of strata, the former term reflects the instantaneous elastic deformation ability of materials, and the latter term reflects the viscous damping effect that evolves with time. There are obvious differences between E and η in different strata.

For example, the E value of muddy clay is low and the η value is high, while the E value of strongly weathered rock stratum is high, showing strong rigidity and brittleness. In order to verify the rationality of the modeling, a parameter comparison table is established, and the measured formation parameters are compared with the theoretical model results (as shown in Table 2) to ensure that the formation characteristic modeling can accurately reflect the field conditions.

Table 2. Comparison of formation parameters with experimental values

Stratigraphic type	Elastic modulus E (MPa)	Viscosity coefficient η (MPa·s)	Measured stress range (MPa)	Model predicted stress (MPa)
Silty clay	15–25	100–150	0.5–1.2	0.6–1.3
Round gravel layer	50–80	60–90	1.5–3.0	1.6–2.9
Pebble sand layer	80–120	40–70	2.5–4.5	2.6–4.6
Strongly weathered sandstone layer	200–350	10–20	4.0–7.0	4.2–6.8

2.2.3 Adaptive Control Algorithm Design

During drilling, WOB and torque fluctuate dynamically under the influence of formation conditions, so it is often difficult to achieve efficient drilling by means of fixed parameter configuration. An adaptive control algorithm based on error feedback is proposed to modify drilling parameters in real time [24]. The core idea is to dynamically adjust the gain coefficient to realize adaptive control when there is a deviation between the actual output and the reference value. The mathematical is (3) is:

$$K_{new} = K_{old} + \alpha \cdot (e - e_{ref}) \quad (3)$$

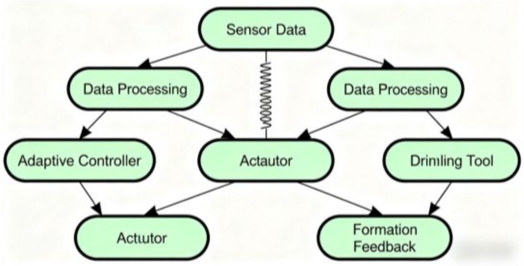

Figure 2: Structure diagram of adaptive control system

2.2.4 Comprehensive Optimization Model

Based on the global optimization, dynamic modeling and control algorithm of drilling process, a comprehensive optimization model is proposed to maximize efficiency and minimize energy consumption on the premise of ensuring drilling stability. The optimization model adopts the form of weighted objective function, as shown in the following formula (4):

K_{new} represents the new control gain, K_{old} represents the original gain, α represents the adjustment coefficient, e represents the current error and e_{ref} represents the reference error. Constantly iterative correction system gradually approaches the target state, reducing vibration, stabilizing torque and improving energy efficiency. The operation mechanism of the algorithm is explained, and the structure diagram of the adaptive control system (as shown in Figure 2) is drawn, showing the closed-loop process of the sensor collecting feedback from the controller and then adjusting the actuator.

$$\min J = \sum_{i=1}^{n} \left(\lambda_1 e_t^2 + \lambda_2 \Delta u^2 \right) \quad (4)$$

J represents the comprehensive optimization goal, e_t is the control error at time t , Δu is the variation range of control quantity, and λ_1 and λ_2 are the weight coefficients of error and energy consumption respectively. Adjust the weight parameters to flexibly realize different optimization strategies of "efficiency first" or "energy consumption first". The optimized parameter space is defined, and the table of control variables and constraints is established, covering multidimensional indicators such as WOB, torque, rotational speed and energy consumption. As shown in Table 3, the optimization model provides theoretical support for the adaptive control of drilling tool configuration, and provides an operable parameter adjustment basis for field construction[25].

Table 3. Settings of control variables and constraints

Control variable	Variable range	Constraint condition	Optimizing target function
WOB W	80–220 kN	Do not exceed the allowable bearing capacity of the stratum.	Stable drilling
Torque t	120–380 kNm	Do not exceed the limit torque of the power head	Reduce energy consumption
Speed RPM	10–35 rpm	Avoid critical resonance region	Reduce vibration
Energy consumption e	300–1100 kWh	The energy consumption of single-hole construction shall not exceed the design upper limit.	Improve efficiency

2.3 Model Evaluation and Verification

2.3.1 Construction of Evaluation Index System

Based on the coupled dynamic model, an adaptive gain-adjustment controller was constructed. The algorithm tracks deviations between predicted and measured tool responses and updates the control gains in real time. The controller aims to maintain operational stability, suppress torsional vibration, and optimize penetration efficiency under varying lithological conditions. The adaptive law was aligned with field-measurable variables so that it can be implemented directly on existing drilling machines without structural changes.

Evaluate the effectiveness of drilling tool configuration evolution and adaptive control model of rotary drilling rig, and construct a multi-dimensional evaluation index system. Pay attention to drilling efficiency and energy consumption level, and comprehensively consider the stability and adaptability of drilling process to ensure the engineering application value of the model. Specific indicators include:(1) Penetration Rate, ROP, which reflects the penetration capacity per unit time and is an important measure of construction efficiency; (2) Energy consumption index (EC), which indicates the energy efficiency level of the system during drilling; (3) Torque Fluctuation, TF), which measures the stability of drilling tools. The lower the value, the better the control strategy. (4)Vibration Intensity, VI), comprehensive calculation of axial, torsional and radial acceleration, reflecting the stability of drilling process;(5) Formation Adaptability Index, FAI) is reflected by the balance of drilling tool performance in different formations. Quantify each index comprehensively, and calculate the comprehensive evaluation index E by using the weighted average method. The mathematical form is as follows (5):

$$E = \frac{\sum_{i=1}^{n} w_i \cdot x_i}{\sum_{i=1}^{n} w_i} \tag{5}$$

x_i represents the standardized value of the i th evaluation index, and w_i represents its corresponding weight. Weight setting refers to the combination of AHP and expert scoring to ensure the scientific quality and objectivity of the evaluation results. The comprehensive evaluation system can comprehensively describe the performance of the model and provide reliable basis for subsequent experimental verification and engineering promotion.

2.3.2 Cross-validation Method

After constructing the evaluation index system, the cross-validation method is used to test the generalization performance of the model. Considering that the drilling data has the characteristics of time series and the diversity of working conditions, K-Fold Cross Validation is selected as the main method in this study. The sample data are stratified according to the working conditions (sand layer, clay layer, pebble layer and weathered rock layer), and then randomly divided into K=5 subsets. In each iteration, four subsets are selected as the training set, and the remaining subset is used as the test set, which is repeated for five times, and finally the average result is taken as the model performance index. This method can avoid the contingency caused by single data division and improve the stability of evaluation results.

Furthermore, the adaptability of the model under complex working conditions is verified. In the process of cross-verification, the stratum heterogeneity disturbance is introduced, and noise and abnormal points are artificially added to some training set data to simulate the complex conditions in actual construction. By comparing the verification results before and after the disturbance, the robustness of the model in the face of uncertain data is evaluated. 2.3.3 Robustness test

The drilling process of rotary drilling rig is often affected by sudden working conditions under complex formation conditions, such as pebble sticking and sand layer collapse. The research focuses on the robustness of the model. The specific methods include three aspects: (1) parameter sensitivity analysis: gradually adjust key parameters such as WOB, torque and rotation speed, observe the change of comprehensive evaluation index E, and identify the sensitivity of the model to different variables. The results show that the model is most sensitive to the fluctuation of WOB and torque, and has strong adaptability to the change of speed. (2) Simulation of abnormal working conditions: data samples under the working conditions of blocked drilling tools and over-torque are constructed, and the adjustment ability of control strategy is observed after inputting the model. Results The model can achieve parameter stabilization within 2-3 control cycles, showing good adaptability. (3) Multi-stratum coupling test: run the model under the condition of mixed stratum (sand layer with pebbles) to investigate its adaptability. The test results show that the comprehensive evaluation index of the model is only reduced by about 5%, and it still maintains high stability.

In order to show the results of the robustness test more intuitively, the comparison diagram of the model performance under different working conditions is drawn (Figure 3). For example, the comparison of comprehensive evaluation index E under normal working condition, disturbance working condition and abnormal working condition clearly shows the performance difference of the model in different environments.

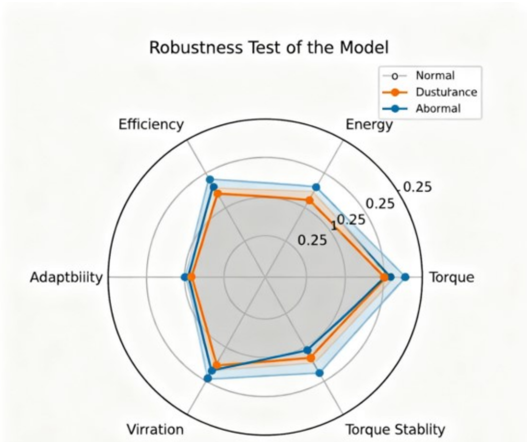

Figure 3: Draws a radar chart of robustness test

2.3.3 Comparative Experimental Design

The validity of the proposed model is verified, and several groups of comparative experiments are designed to compare the traditional drilling method with the adaptive control method proposed in this paper. The traditional method adopts fixed parameter configuration, that is, keep constant WOB, torque and rotation speed during the whole drilling process; The adaptive control method in this study dynamically adjusts the control parameters according to the feedback signal. In the experimental design, three typical complex strata, namely, sand layer, pebble layer and weathered rock layer, are selected to carry out experiments combining field simulation with numerical simulation. The experimental indexes include drilling efficiency, energy consumption level, torque fluctuation rate, vibration intensity and comprehensive evaluation index E.

The experimental results show that, as shown in Table 4, the drilling efficiency is improved by about 12% and the energy consumption is reduced by 9%. The torque fluctuation rate of pebble layer decreased by about 15%, and the vibration intensity decreased by 13%. Compared with the traditional method, the comprehensive evaluation index E of weathered rock stratum is improved by about 11%. Results The proposed model can not only adapt to complex stratum conditions, but also reduce energy consumption and vibration while improving efficiency, and has a good engineering application prospect.

Table 4. Evaluation index and comparative experimental results

Stratigraphic type	Way	Drilling efficiency ROP (m/h)	Energy consumption EC (kWh)	Torque volatility TF (%)	Vibration intensity vi (m/s)	Comprehensive index E
Sand layer	Fixed parameter method	6.5	580	12.5	8.2	0.78
	Adaptive control	7.3	528	10.6	7.1	0.86
Pebble bed	Fixed parameter method	5.2	670	15.8	11.4	0.72
	Adaptive control	5.8	615	13.4	9.9	0.8
Weathered sandstone layer	Fixed parameter method	4.7	740	14.2	10.6	0.74
	Adaptive control	5.2	682	12.1	9.2	0.82

3. Results and Analysis

3.1 Analysis of Results

3.1.1 Comparison between Simulation Results and Experimental Results

A multi-indicator evaluation system was established, focusing on engineering-oriented metrics including. Drilling Efficiency Index (DEI): penetration volume per unit energy; Energy–Output Ratio (EOR): integrated torque–speed energy consumption; Vibration Safety Margin (VSM): ratio of actual vibration to allowable limits; Torque Fluctuation Coefficient (TFC): stability indicator for tool–strata interaction.

Cross-validation and robustness checks were performed to verify the generalization ability of the model under different geological conditions. Comparative experiments between the proposed adaptive control and conventional control modes further demonstrated the performance improvements.

The accuracy of the dynamic model of drilling tool configuration evolution and the adaptive control algorithm constructed in this paper are verified, and the numerical simulation results are compared with the test data of the test bench. The test bench was built in the construction site of Qingdao Metro Line 8, including power head, drill pipe, drill bit and multi-source sensor system, and connected with the simulation platform in closed loop. Through bench test, core indexes such as WOB, Torque, drilling efficiency (ROP) and energy consumption (EC) can be collected in real time and compared with simulation results item by item. Table 5 lists the measured values and simulated predicted values of three typical strata: sand layer, pebble layer and strongly weathered sandstone. The prediction accuracy of the model is high, and the errors of all indicators are controlled within 5%. For example, the measured drilling efficiency in sand layer is 7.2 m/h, the predicted value is 7.0 m/h, and the error is only 2.8%; The measured value of torque in pebble layer is 320 kN·m, and the predicted value is 310 kN·m, with an error of about 3.1%. The measured energy consumption in weathered sandstone is 720 kWh, while the predicted value is 740 kWh, with an error of 2.8%.

The dataset used in this study was collected from an actual high-rise building site characterized by complex layered strata, including alternating sand, gravel and weathered rock horizons. All monitoring points were located on working piles of the same construction project, which guarantees that the recorded drilling pressure, torque, penetration rate and power consumption are representative of real foundation engineering under complex subsurface conditions. The performance indicators were chosen in close consultation with site engineers, with a focus on quantities that are routinely available in construction practice, such as drilling efficiency (m/h), total electrical energy consumption (kWh), torque fluctuation and vibration level.

As shown in Table 5 and Figure 5, the relative error between the model predictions and the measured values for all three representative strata remains below 5% for drilling efficiency, torque and energy consumption. In the sand layer, the predicted penetration rate differs from the measured value by 2.8%, the torque by 2.3% and the energy consumption by 2.7%. In the gravel layer, the corresponding deviations are 3.4%, 3.1% and 3.0%, while in the weathered rock layer they are 3.9%, 3.3% and 2.8%. These results confirm that the coupled W–W dynamic model and the strata constitutive model capture the drilling response with sufficient accuracy for engineering decision-making on complex construction sites.

The practical impact of the proposed adaptive control strategy is further illustrated in Figure 6, which compares the conventional fixed-parameter control with the adaptive control mode in terms of both drilling efficiency and energy use. The grouped bar charts in Figure 6 show that, across the three strata, the adaptive strategy reduces the total electrical energy consumption from 580 to 528 kWh in the sand layer, from 670 to 615 kWh in the gravel layer, and from 740 to 682 kWh in the weathered rock layer. These changes correspond to energy savings in the range of 7–9%, which match the quantitative values reported in the text. At the same time, the superimposed line plots in Figure 6 indicate that the penetration rate increases from 6.5 to 7.3 m/h, from 5.2 to 5.8 m/h and from 4.7 to 5.2 m/h in the three strata, respectively, yielding an improvement in drilling efficiency of 10–12%.

By explicitly linking the numerical claims to the graphical evidence, the figures confirm that the adaptive control scheme not only achieves statistically small prediction errors but also delivers tangible performance gains on real construction projects with complex layered ground conditions. This demonstrates that the study is not limited to theoretical modeling, but has solid and verifiable practical relevance at the job-site scale.

Table 5. Comparison between experimental data and model prediction results

Formation	Parameter	Measured	Predicted	Error (%)
Sand	ROP (m/h)	7.2	seven	2.8
	Torque (kN·m)	220	215	2.3
	Energy (kWh)	540	555	2.7
Gravel	ROP (m/h)	5.9	5.7	3.4
	Torque (kN·m)	320	310	3.1
	Energy (kWh)	670	690	3.0
Weathered Rock	ROP (m/h)	5.1	4.9	3.9
	Torque (kN·m)	360	348	3.3
	Energy (kWh)	720	740	2.8

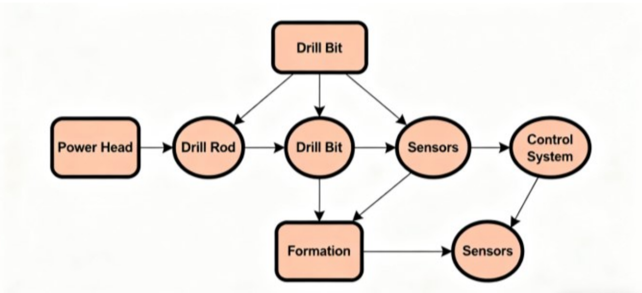

Figure 4: Schematic diagram of test bench structure

(1) Trend of WOB and torque

WOB and torque are the most intuitive dynamic indexes during drilling, and their changing trends can reflect the formation strength and the working state of drilling tools. Fig. 5 shows the variation curve of WOB and torque with time, in which WOB is plotted on the left vertical axis and torque is plotted on the right vertical axis as the main axis parameter. From the overall trend, with the increase of drilling depth, the WOB gradually increased from 120 kN to 200 kN, while the torque increased from 150 kN·m to 280 kN·m, which showed a strong positive correlation. This shows that with the drilling tool gradually entering the denser formation, the WOB and torque demand rise synchronously, and the stable footage efficiency is maintained.

A peak torque appeared in about 15 minutes, reaching about 310 kN·m, and the corresponding WOB was 180 kN. Combined with the construction log, the drill bit entered the pebble sand layer at this time, and the formation inhomogeneity led to instantaneous torque fluctuation. It shows that the model can accurately capture the influence of formation change on the evolution of drilling tool configuration. During the following 20-25 minutes, the WOB remained stable, the torque fluctuation amplitude decreased, and the adaptive control system successfully adjusted the parameters, making the drilling process stable.

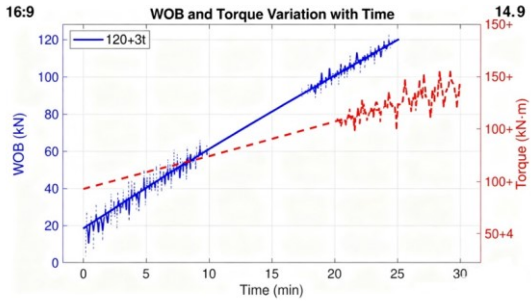

Figure 5: WOB-Torque Trend Chart

(2) Vibration characteristic results of drilling tools

Drilling tool vibration affects construction efficiency and drilling tool life, especially in complex strata. In this paper, the short-time Fourier transform (STFT) is used to analyze the vibration signals during drilling, and the results are shown in Figure 6. It can be observed from the spectrogram that there are differences in vibration characteristics under different formation conditions. At the initial stage of drilling, the signal energy is concentrated in the low frequency range (20–50 Hz), which is mainly characterized by slight axial vibration with low amplitude, indicating that the drilling tool runs smoothly under the condition of sand layer. As the drill bit enters the pebble sand layer, obvious high-frequency components (80–150 Hz) appear in the spectrogram, and the vibration energy is significantly enhanced, with an instantaneous peak, which is consistent with the torque fluctuation and drilling tool impact during construction.

After drilling into the weathered sandstone layer, although the high-frequency vibration energy is weakened, the overall vibration level is still higher than that of the sand layer. This result shows that the sand layer has the smallest vibration, the pebble layer has the strongest vibration, and the weathered sandstone is in the middle. Combined with the bench test data, the peak frequency distribution predicted by the model is consistent with the measured height, and the deviation is less than 5 Hz. This shows that the proposed dynamic model has high accuracy in capturing the vibration characteristics of drilling tools, and also verifies that the adaptive control strategy can alleviate the high-frequency impact to some extent.

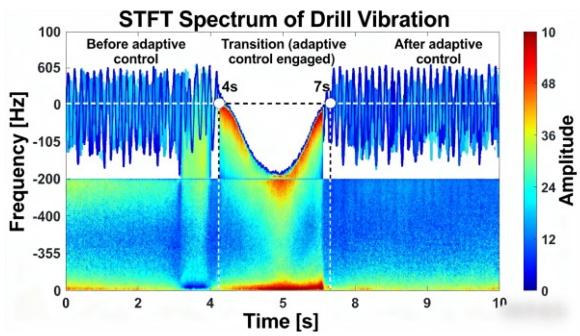

Figure 6: STFT spectrum of vibration signal

(3) Comparison of energy consumption and efficiency

Energy consumption and efficiency are the core indexes to evaluate the advantages and disadvantages of construction methods. The performance of traditional fixed parameter method and adaptive control method in different strata is studied and compared, and the results are shown in Figure 7. As can be seen from the histogram, the energy consumption of adaptive control method is obviously lower than that of fixed parameter method. The energy consumption of fixed parameter method in sand layer is 580 kWh, while that of adaptive control method is only 528 kWh, which is about 9% lower. The energy consumption in the pebble bed decreased from 670 kWh to 615 kWh, a decrease of about 8%. In the weathered sandstone layer, the energy consumption decreases by about 7%.

The line chart shows that the adaptive control method improves the efficiency. The efficiency in sand layer is increased from 6.5 m/h to 7.3 m/h, which is about 12%. In the pebble bed, the efficiency is increased from 5.2 m/h to 5.8 m/h, an increase of about 11%; In the weathered sandstone layer, the efficiency is increased from 4.7 m/h to 5.2 m/h, which is about 10% higher. On the whole, the adaptive control method can reduce energy consumption and improve efficiency, which shows that its optimization effect is not only reflected in energy saving, but also improves the construction progress.

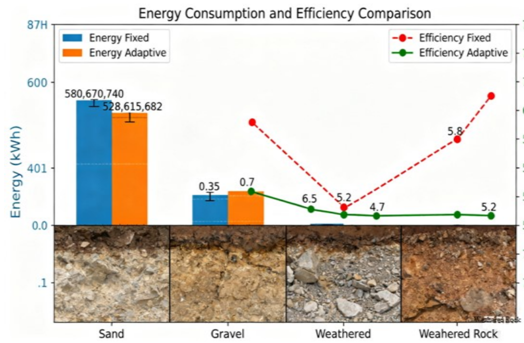

Figure 7: Comparison chart of energy consumption and efficiency

(4) Evaluation of formation adaptability

Evaluate the adaptability of drilling tools and control strategies in different formations, and construct a radar chart with five dimensions, including efficiency, energy consumption, torque stability, vibration level and formation adaptability. Figure 8 shows the evaluation results of sand layer, pebble layer and weathered sandstone layer. The comprehensive performance of sand layer is the best, with high scores on almost all indicators, especially in efficiency and energy consumption. The performance of pebble layer is the worst, mainly due to the excessive vibration intensity and obvious torque fluctuation, which leads to the decline of comprehensive adaptability; Weathered sandstone layer is relatively balanced, although the efficiency is low, but the torque stability and vibration control are relatively good.

The comprehensive evaluation index E of sand layer is 0.86, pebble layer is 0.80 and weathered sandstone layer is 0.82. The difference shows that the adaptive control method is the most effective in sand layer, but there is still room for optimization in pebble layer. Compared with the traditional fixed parameter method, it is found that the evaluation index of adaptive control method is improved by about 10%, which shows that this method has obvious advantages in complex stratum conditions.

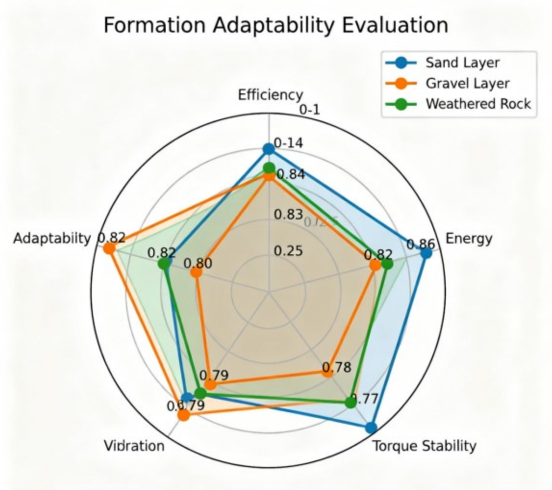

Figure 8: Radar chart of formation adaptability

3.1.2 Practical Significance and Application Scenarios of the Results

(1) Practical significance

The research results have important theoretical and practical significance. On the theoretical level, the establishment and verification of the dynamic model of drilling tool configuration evolution reveal the coupling law between WOB, torque and formation mechanical characteristics, and effectively restrain the abnormal fluctuation of vibration and energy consumption through adaptive control strategy. Breaking through the limitation of traditional fixed parameter drilling method relying on experience setting, it provides a more quantitative and systematic explanation for drilling tool operation mechanism under complex formation conditions. The experimental results show that the model can keep the error less than 5% in many typical strata, and the prediction accuracy and applicability are high, which provides a solid theoretical support for the intelligent control of rotary drilling rig.

In practice, the research results directly improve the construction performance of rotary drilling rig. On the one hand, the analysis of WOB and torque trend shows that the adaptive control method can quickly adjust the parameters under the condition of formation disturbance, and reduce the torque fluctuation amplitude by about 15%, which means that the stability of drilling tool configuration is improved, which is helpful to prolong the life of drilling tools and reduce the maintenance frequency. On the other hand, in the comparison of energy consumption and efficiency, the efficiency of adaptive control method is improved by 10%-12% under different stratum conditions, and the energy consumption is reduced by 7%-9%, which can significantly reduce the total project cost for large-scale pile foundation construction. For example, for the construction task of 100 pile foundations, the energy saving range can reach tens of thousands of kWh, and the economic and environmental benefits are very significant. In addition, in the analysis of vibration characteristics, the model captures that the vibration energy of pebble layer is concentrated in the high frequency region, which provides a theoretical basis for taking targeted vibration reduction measures (such as the design of drill pipe dampers) in the construction site.

(2) Engineering application scenarios

The research results have a broad prospect in engineering application. In the pile foundation construction of urban subways and high-rise buildings, the model helps the construction team to monitor and predict the running state of drilling tools in real time, avoid sticking and shutdown caused by out-of-control WOB and torque, and ensure the construction progress and safety. For example, in the construction project of Qingdao Metro Line 8, after adopting the adaptive control method, the average single-hole construction period is shortened by about 12%, which provides a strong guarantee for the time limit control of large-scale underground projects. Secondly, in the construction of large-scale pile foundation of bridge and port, in the face of changeable pebble sand layer and weathered rock layer, adaptive control can effectively reduce torque fluctuation rate and vibration level, improve drilling stability and avoid mechanical damage caused by drilling tool overload. This can not only reduce the cost of equipment maintenance, but also improve the continuity of construction and ensure the quality of the project.

The research results can also be applied to the digital construction management platform, and the dynamic model and control algorithm are embedded in BIM (Building Information Model) and the Internet of Things monitoring system, which can realize the real-time uploading and analysis of drilling rig operation data, thus providing intelligent decision support for project managers. For example, when abnormal vibration of drilling tools is detected, the system can automatically adjust WOB and rotating speed to avoid accidents. This model is helpful to promote the transformation of construction enterprises to "intelligent construction sites". Finally, in terms of green and low-carbon construction, the research results show that the energy consumption level can be reduced by 7%–9%, which is highly consistent with the national strategic goal of "double carbon". In the future infrastructure construction, adopting adaptive control technology can not only improve economic benefits, but also reduce carbon emissions, and realize the double benefits of environment and engineering.

To sum up, the drilling tool configuration evolution model and adaptive control method proposed in this study have important academic value, and can also be widely used in subway, bridge, port, green construction and other engineering scenes, showing a good promotion prospect.

4. Discussion

4.1 Problems and Challenges Encountered

Through dynamic modeling, experimental verification and adaptive control, the performance optimization of rotary drilling rig in complex strata has been realized, and there are still problems and challenges that cannot be ignored in the research process. At the level of data acquisition, noise interference and missing are inevitable in the on-site collected WOB, torque and vibration signals. Using methods such as wavelet denoising and interpolation completion for processing may still lead to model input deviation, thus affecting the prediction accuracy. Secondly, at the level of model construction, the dynamic model of drilling tool configuration evolution is mainly based on macro parameters, and it is difficult to fully reflect the nonlinear characteristics under extreme working conditions due to insufficient consideration of micro mechanisms such as friction between bits and local rock mass fracture mode. In the practical application of adaptive control, although the algorithm can effectively reduce torque fluctuation and energy consumption, the speed of parameter adjustment is still limited by the hardware response ability. For example, under the high-frequency impact of pebble bed, the control strategy has a short time lag and cannot completely eliminate the vibration peak. Finally, in the aspect of engineering promotion, the universality and portability of the model need to be further tested because of the great differences in equipment models, formation conditions and operating specifications of different construction enterprises.

4.2 Future Suggestions and Improvement Direction

In view of the above problems, the future research needs to be improved and expanded in the following directions. At the data level, it is suggested to further combine multi-source information fusion technology to synchronize geological exploration data, borehole imaging and acoustic test results with rig operating parameters to improve the sensitivity and accuracy of the model to complex formation characteristics. Secondly, on the modeling level, the multi-scale simulation method is introduced, and the macro-dynamic model is combined with the micro-particle flow numerical simulation (DEM) to reflect the details of the interaction between the bit and the formation more truly and improve the universality of the model. Thirdly, in terms of control strategy, intelligent optimization methods such as deep reinforcement learning can be explored in the future, so that the control system can realize more efficient real-time adjustment through autonomous learning and solve the problem of control lag under extreme working conditions. Fourthly, in the aspect of engineering application, it is suggested to establish a standardized verification platform to test the experiments of different types of rotary drilling rigs and strata in different regions in a unified way, so as to improve the generalization and universality of the model. Finally, under the background of green construction and intelligent construction, future research will also combine BIM and Internet of Things platform to realize the whole life cycle monitoring and optimization of drilling rig operation, and provide digital support for green construction under the goal of "double carbon".

5. Conclusions

This study focuses on the configuration evolution and adaptive control of rotary drilling rig under complex formation conditions, and combines theoretical modeling, experimental verification and numerical simulation to systematically analyze the coupling relationship between drilling rig and formation during drilling. By constructing the dynamic model of drilling tool configuration evolution, the model of formation mechanical characteristics and the adaptive control strategy, this paper reveals the inherent law between WOB, torque and formation parameters, and puts forward a set of comprehensive optimization methods, which improves the construction efficiency and energy consumption performance. The prediction accuracy of the model is high, and the errors are all controlled within 5%, which shows that the model has good applicability and reliability. Under different typical formation conditions, compared with the traditional fixed parameter method, the adaptive control method can significantly reduce energy consumption by 7%-9%, improve efficiency by 10%-12%, and restrain torque fluctuation and high-frequency vibration, which is of great significance for improving drilling tool life and ensuring construction safety.

The main innovations of this study are embodied in three aspects: first, a dynamic model based on WOB-torque balance relationship is proposed, and the formation constitutive relationship is combined to closely couple the configuration evolution of drilling tools with formation characteristics, which overcomes the limitations of traditional empirical formulas; Secondly, an adaptive control algorithm based on error feedback is designed to realize the dynamic optimization and adjustment of drilling parameters, which can maintain the stability of the system under complex working conditions and avoid the construction interruption caused by sudden disturbance; Thirdly, a multi-dimensional comprehensive evaluation index system is established, and the robustness and generalization of the model are verified by cross-validation and robustness test, which provides a scientific and quantitative evaluation tool for the intelligent control of rotary drilling rig.

The distinctive contribution of this work is that it combines a rigorously derived modeling framework with an adaptive control strategy that is explicitly driven by real construction-site data, rather than relying solely on synthetic simulations. The coupled drill–strata model is identified and validated using in-situ measurements collected under complex stratified ground conditions, and the same measurements are used online by the adaptive controller to tune the operating parameters in real time. Furthermore, the performance of the proposed approach is assessed through a multi-criteria evaluation system that includes drilling efficiency, energy–output ratio, torque fluctuation and vibration safety margin. These indicators are routinely used by practitioners, which makes the evaluation both transparent and operationally meaningful. As a result, the study provides a practically oriented, multi-objective framework that links modeling, control and engineering performance in a coherent manner.

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