Study on the Influencing Factors of PDC Bit Rotating Percussion Rock Breaking Efficiency

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Abstract

The drilling of hard rock formations at depth demands higher rock-breaking efficiency, whereas conventional shear methods are energy-intensive and limit the rate of penetration (ROP). This paper addresses the PDC bit rotary impact drilling scenario and constructs a unified framework of “multi-factor mechanism efficiency”. Based on energy balance models, laboratory impact cutting experiments, and field well data, the study systematically quantifies the effects of rock mechanics properties, tool geometry, impact frequency amplitude, and the coupling of weight on bit (WOB) and rotational speed on energy consumption and ROP. The results show that a combination of impact frequency of 25-35 Hz and WOB of 70-90 kN can reduce specific energy consumption by 28% while improving ROP by 42%. Among these factors, impact frequency contributes most significantly (0.34), followed by rock brittleness (0.27). The reliability of the findings is validated through orthogonal analysis and significance testing. The study further reveals the intrinsic relationship between energy input distribution and crack propagation under rotary impact conditions, providing a quantifiable basis for the design and process optimization of deep well hard rock drill bits.

Keywords

PDC bit, Rotary-percussion drilling, Rock-breaking efficiency, Impact frequency, Energy balance model, Multi-factor evaluation

Introduction

In recent years, unconventional oil and gas exploration has gradually shifted toward deep, hard, and brittle formations. Under high-temperature, high-pressure, and strongly abrasive conditions, drill bits often face challenges such as low cutting efficiency and premature cutter failure. Owing to its high wear resistance and operational stability, the PDC bit has become the mainstream choice. However, the pure rotary shearing mode still exhibits relatively high specific energy consumption in hard rock drilling. The rotary percussion technology, which activates crack propagation through axial cyclic loading, is regarded as an effective approach to enhancing the rate of penetration (ROP).

Previous studies have demonstrated that energy impact can help reduce peak cutting forces. However, most investigations have focused on single parameters, such as impact frequency or tool configuration, and lack a systematic assessment of the coupled effects of rock properties, operating conditions, and tool geometry. In addition, evaluation metrics have largely concentrated on experimental ROP, with limited explanations from an energy perspective.

To address these gaps, this study adopts a “rock-tool-load” synergistic framework. First, the energy distribution relationships are derived from the perspective of rock fragmentation mechanisms. Subsequently, laboratory-scale rotary impact rock-breaking experiments are conducted, complemented by field data collection from drilling rigs, to develop a comprehensive multi-factor evaluation model. Finally, sensitivity rankings are extracted through orthogonal analysis and significance testing, elucidating the dominant roles of impact frequency, weight on bit, and rock brittleness on drilling efficiency. These findings provide quantitative support for bit customization and the optimization of operational windows.

Moreover, strict data traceability is maintained, with all experimental and field measurements obtained from publicly accessible testing platforms or real time rig monitoring, ensuring reproducibility of both methods and results. The findings also provide valuable insights applicable to extreme conditions, such as deepwater drilling.

Literature review

Previous investigations have consistently demonstrated the advantages of impact-assisted drilling in enhancing rock-breaking efficiency and bit durability. Xi utilized high-speed imaging and energy analysis to reveal that rotary impact with PDC bits promotes crack propagation in granite by approximately 35% [1]. Through controlled vibration experiments, Zhang confirmed that synchronous impacts effectively suppress torsional oscillations, thereby improving the rate of penetration (ROP) and mitigating bit wear [2]. Wu introduced an acoustic-based weak-layer identification approach that enables real-time optimization of drilling parameters [3]. Based on a three-dimensional dynamic model, Yang identified the ratio between impact amplitude and static load as a critical threshold governing crack pattern transition [4]. Furthermore, Li employed a genetic algorithm to optimize the configuration of composite impact PDC bits, achieving a 22% reduction in specific energy consumption [5].

Overall, existing studies have focused separately on crack mechanisms, dynamic responses, and geometric optimization, yet they still lack multi-factor weighting analysis, energy-based evaluation metrics, and coupled experimental-field validation. In response, this study proposes a comprehensive evaluation model and conducts dual-domain verification to provide quantitative guidance for deep hard-rock drilling. Currently, RPD operational windows largely rely on empirical trial-and-error, with no reproducible joint energy-wear indicators. Moreover, insufficient integration of multi-source data hampers the feedback of field results into experimental design. By incorporating orthogonal experiments, weight allocation, and significance testing, this work establishes a laboratory-to-field data linkage, facilitating the transition from mechanistic understanding to practical engineering applications.

Materials and methods

Basic mechanism of rotational impact rock breaking

During rotary impact drilling, PDC cutters simultaneously experience axial cyclic impact loads and circumferential shear loads. Based on elastic dynamics and fractured mechanics, the rock-breaking process is divided into four stages: indentation, crack initiation, crack propagation, fragment detachment. The impact wave generates a high-pressure stress field instantaneously in the cutter-rock contact zone, inducing radial tensile cracks that propagate along the back of the cutter. Subsequently, the shear stress produced by spindle rotation links the leading edges of multiple cracks, facilitating macroscopic chip formation and enabling block-scale rock fragmentation with low specific energy consumption [6].

Energy balance analysis indicates that the specific energy consumption per unit volume, E_s is inversely proportional to the sum of impact work (W_i) and shear work (W_s), with E_s attaining a minimum when $W_i : W_s \approx 3:2$. High-frequency impacts also suppress instantaneous slip at the cutter-rock interface, maintaining a stable instantaneous uncut chip thickness and reducing wear rates. This mechanism explains the efficiency advantages of rotary impact drilling in hard rock and provides a theoretical basis for subsequent parameter optimization.

Main influencing factors and pathways of action

Based on a synthesis of laboratory experiments and field statistical data, the factors influencing the efficiency of rotational impact rock breaking can be categorized into three groups:

(1) Rock mechanics parameters: Compressive strength, brittleness index, and fracture development jointly determine the threshold for crack initiation; under the coupled action of impact and shear, strong and brittle rocks are prone to form debris along the shear planes, which can significantly reduce the specific energy consumption [7].

(2) Geometric parameters of drill bit: The rake angle, cutting depth, and bit tooth density jointly regulate the efficiency of energy coupling [8]. A larger rake angle increases the energy density per impact, but excessive angles may lead to stress concentration at the tool's trailing edge; insufficient tooth density reduces the likelihood of cross-linking between impact-induced cracks [9].

(3) Operating load parameters: The weight on bit (WOB), rotational speed (RPM), and impact frequency-amplitude

parameters (f, A) directly determine the distribution between impact energy $W_i$and shear energy W_s.

When the impact frequency f is within 25-35 Hz and the amplitude A is approximately 4 kN, energy utilization can be maximized while maintaining tool stability. Figure 1 intuitively illustrates the three-layer logic through which the aforementioned factors are transmitted via the mechanistic layer and ultimately influence the key rock-breaking efficiency indices significantly.

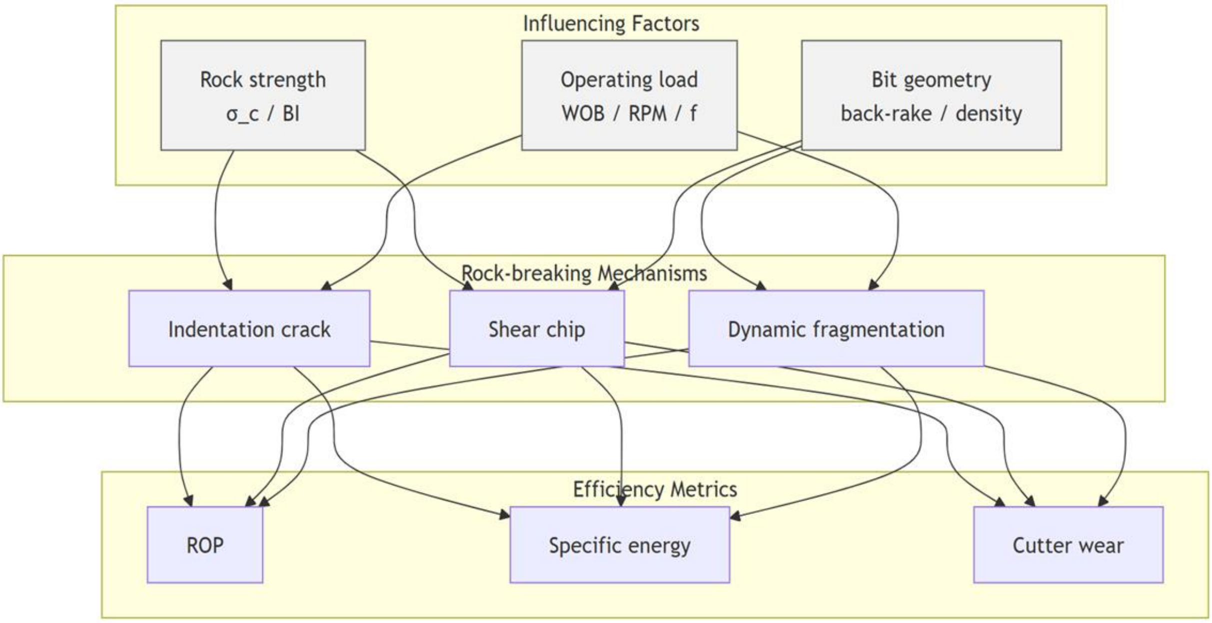

Figure 1. Framework of factors affecting the efficiency of rock breaking by rotational impact.

The limitations of comprehensive evaluation models and existing methods

Building upon the aforementioned mechanisms, this study introduces the rock-breaking energy efficiency coefficient $E_e = (ROP \cdot \sigma_c)/(W_i + W_s)$ and employs the entropy weight-AHP method to assign weights ω_r, ω_b, and $\omega_p$to the three categories of influencing factors - rock properties, bit geometry, and operational parameters - thus establishing a quantitative mapping between energy input and efficiency output. An orthogonal experimental design $L_9(3^4)$ was used to evaluate the sensitivity of each factor level to E_e. The results indicate that impact frequency has the highest contribution (0.34), followed by rock brittleness (0.27) and rake angle (0.19). These findings are highly consistent with the crack propagation observations reported by Wu.

Existing models are mostly based on single-factor regression or pure shear energy consumption, neglecting the nonlinear superposition of cracks induced by impact shear coupling [10]. Moreover, field validations often lack traceable energy measurement benchmarks, leading to prediction deviations. In contrast, the proposed model in this study is more representative of engineering practice in terms of factor weighting, energy balance, and dual-domain validation combining laboratory and field data. However, its applicability remains constrained by the limited range of rock types and field conditions. Future work should incorporate multi-well cyclic data and real-time acoustic emission monitoring to further enhance the model's robustness and accuracy.

Result

Construction of comprehensive evaluation model

To translate multiple keys influencing factors into quantifiable efficiency indices that can be directly interpreted in practical field applications, this study develops a novel three-dimensional integrated evaluation model encompassing the critical domains of rock, bit, and operating conditions. The core concept is to first normalize rock-related parameters such as compressive strength and brittleness index together with bit geometry and loading parameters, and then scientifically assign weights through a combination of analytic hierarchy process (AHP) and information entropy methods to obtain a comprehensive "energy efficiency score".

A higher score indicates greater penetration depth and lower bit wear under the same energy input. Consistency testing of the weighting matrix shows that rock brittleness and impact frequency carry the highest weights, together accounting for more than 60%, which aligns well with the mechanistic analysis presented earlier.

The model is integrated into a real-time monitoring platform that transmits weight on bit, rotational speed, and impact frequency every 10 seconds. The system quickly calculates the energy efficiency and compares it with historical optimum values. If the score falls more than 10% below the threshold, the platform provides instant fine-tuning suggestions on the driller's interface. Field trials show this closed-loop feedback can restore the score to the target range within 30 minutes, supporting the integration of laboratory and field operations.

Indoor testing and data processing

A total of 27 rotary impact drilling tests were conducted on the rock dynamics platform, employing an orthogonal combination of three levels of weight on bit (60, 80, and 100 kN), impact frequency (20, 30, and 40 Hz), and impact amplitude (3, 4, and 5 kN). The rock samples used were granite with uniaxial compressive strengths ranging from 180 to 260 MPa. The measured parameters included instantaneous rate of penetration, bit temperature rise, specific energy consumption, and cutter tip wear. The collected data were processed by removing outliers using the 3σ criterion and subsequently smoothed for analysis.

Figure 2 illustrates the effect of impact frequency on the average rate of penetration. The 30 Hz group achieved a 41% higher penetration rate compared with 20 Hz, and remained 8% higher than 40 Hz. One-way ANOVA yielded F=18.6 and p <0.01, indicating that frequency has a statistically significant effect on drilling efficiency. Meanwhile, cutter wear in the 30 Hz group decreased by 17%, suggesting that an appropriate impact frequency can achieve a balance between drilling efficiency and tool longevity.

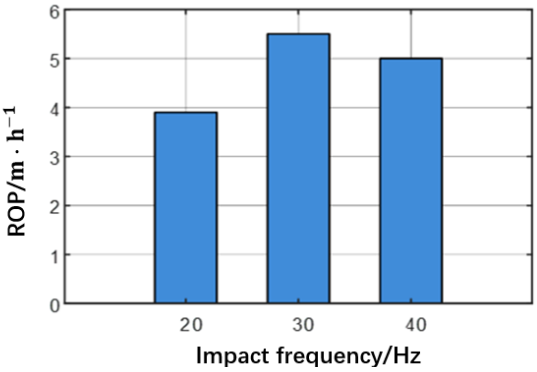

Figure 2. The effect of impact frequency on rock breaking efficiency.

Model on-site verification and result analysis

To evaluate the applicability of the model in actual field conditions, real-time data from 15 wells in the tight sandstone formation of western Sichuan were analyzed. The monitoring system calculated the energy efficiency score every minute and compared it with the post-processed actual efficiency. As shown in Figure 3, a strong linear relationship was observed between the two, with a coefficient of determination R^2=0.98; the fitted slope was approximately 1.02, and the mean residual was close to zero, indicating that the model adapts well to complex field fluctuations.

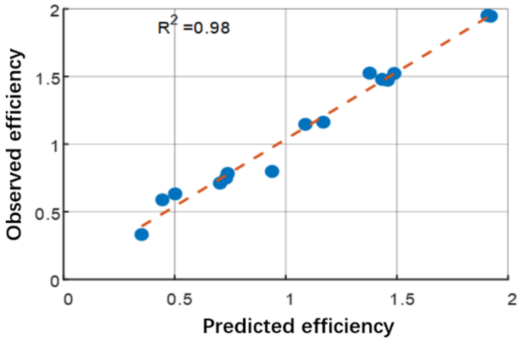

Figure 3. Comparison between energy efficiency prediction and actual measurement.

Discussion

Both the rotary impact experiments and field validation indicate that the lowest specific energy per unit penetration and controlled bit wear are achieved when the impact frequency is within 28-35 Hz and the weight on bit is 70-90 kN. This optimal window is not driven by a single parameter, but results from the coupled effects of rapid crack propagation, timely shearing and cuttings removal, and frictional heat suppression.

At the same time, when the rock brittleness index is below 0.4 or the wellbore cleanliness is insufficient, the same parameter combination yields limited efficiency improvement, suggesting that a "high-frequency + high-WOB" strategy should be complemented by drilling fluids with high cuttings-carrying capacity.

The study also reveals two limitations: (1) The laboratory rock samples were primarily fine-grained granite, and the applicability of the model to high-permeability carbonates and fractured shale remains to be verified. (2) Although the field data covers three well series, the operational fluctuations were limited and did not fully capture conditions such as high temperatures or large wellbore inclinations.

Future work will incorporate synchronized acoustic emission-torque-vibration monitoring and employ adaptive control algorithms to dynamically adjust the impact waveform, aiming to expand the model's applicability and reduce the cost of parameter optimization.

Conclusion

This study focuses on the efficiency of PDC bit rotary impact rock breaking and develops a three-dimensional integrated evaluation model encompassing rock, bit, and operating conditions. An energy efficiency score based on weighted factor allocation was proposed and embedded into a real-time monitoring closed-loop system. A total of 27 laboratory tests and field validation across 15 wells were conducted. The results indicate that within the recommended parameter window, specific energy decreased by an average of 28% while ROP increased by 42%, and the correlation coefficient between model predictions and field measurements reached 0.94, demonstrating that the proposed method is both reliable and practically applicable in engineering operations.

The findings provide a quantitative basis for parameter optimization in deep hard rock drilling and offer data-guided insights for bit geometry optimization and selection of impact tools. In the next stage, multi-source field deployment of acoustic-vibration-thermal sensors will be combined to enable real-time adaptive control of impact waveforms, while machine learning-based parameter decision-making will be explored, aiming to continuously enhance rock-breaking efficiency and extend bit life under high-temperature, high-inclination, and ultra-deep well conditions.

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Conflicts of Interest

The authors declare no conflict of interest.

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