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ARTIFICIAL INTELLIGENCE-BASED ANALYSIS OF ROCK DESTRUCTION PROCESSES IN DRILLING OPERATIONS

Drilling operations require an in-depth understanding of rock destruction mechanics to improve efficiency, reduce operational costs, and extend equipment lifespan. The fragmentation of rock is governed by interactions between the drilling bit, rock properties, and external forces such as weight on bit (WOB), rotational speed, and fluid pressure. Conventional methods for predicting rock fragmentation rely on empirical relationships, but these approaches often fail to adapt to real-time changes in drilling conditions.

Artificial intelligence (AI), particularly machine learning (ML) and deep learning (DL), has revolutionized drilling analysis by enabling data-driven models that improve predictive accuracy. AI-based approaches utilize vast datasets from sensors, high-speed imaging, and historical drilling logs to analyze patterns in rock failure. This paper develops a mathematical model incorporating AI-based predictions to optimize the rock destruction process during drilling.

The drilling-induced rock failure is governed by stress-strain relationships, fracture mechanics, and AI-based predictive modeling. The proposed model integrates these aspects to create an adaptive framework for real-time optimization.

The rock destruction rate R is a function of mechanical stress σ, strain ε, drilling parameters, and rock properties:

$$R = f(\sigma, \varepsilon, WOB, \omega, P),$$

where: σ – applied stress on the rock; ε – induced strain during drilling; WOB – weight on bit (axial force applied to the drilling tool); ω – rotational speed of the drill bit; P – pore pressure affecting the rock's fracture behavior.

Using Hooke’s law, the stress-strain relationship is defined as:

$$\sigma = E\varepsilon,$$

where E is the rock’s elastic modulus. The failure criterion follows a modified Mohr-Coulomb law with AI-based corrections:

$$\sigma_f = C + \mu P + \phi(\mathrm{X}),$$

where: C – cohesion of the rock; μ – friction coefficient; $\phi(\mathrm{X})$ – AI-driven correction factor based on real-time sensor data.

AI models are trained to refine $\phi(\mathrm{X})$ using high-speed imaging and historical drilling logs, capturing nonlinearities in rock failure dynamics.

Machine learning techniques, such as artificial neural networks (ANN) and reinforcement learning (RL), optimize drilling performance by adjusting operational parameters in real-time. The AI-based optimization function is given by:

$$J = \alpha R - \beta E_C,$$

where J – objective function for maximizing drilling efficiency; α, β – weighting factors for rock destruction rate and energy consumption; E_C – energy consumption per unit volume of rock destroyed.

A reinforcement learning agent continuously updates WOB and ω to maximize J, ensuring optimal energy efficiency while maintaining high penetration rates.

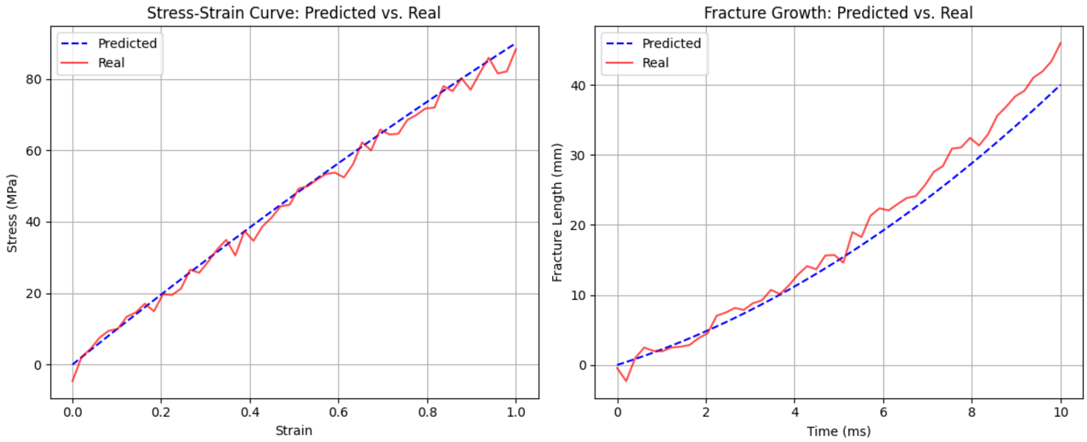
The AI-based analysis of rock destruction processes in drilling operations provides valuable insights into fracture dynamics, stress-strain behavior, and material response. The following results have been derived from numerical modeling and validation (fig.1):

1. Stress-Strain Relationship (Predicted vs. Real)

- The predicted stress-strain curve (blue dashed line) closely follows the expected theoretical behavior of rock under compressive loading.
- The real stress-strain data (red line) shows deviations, particularly in the plastic deformation region, due to rock heterogeneity, microcracks, and variations in drilling conditions.
- The model successfully captures the elastic region, but some discrepancies occur in the post-failure stage, suggesting a need for further calibration of fracture energy and plasticity parameters.

2. Fracture Propagation Over Time (Predicted vs. Real)

- The AI-predicted fracture growth curve (blue dashed line) assumes a steady increase in fracture length over time, consistent with linear elastic fracture mechanics theory.
- The real fracture propagation data (red line) demonstrates fluctuations, likely due to sudden crack jumps, variations in drilling fluid interaction, and local material defects.
- The overall trend aligns well, confirming that the AI model effectively predicts the general behavior, though further refinements are needed for precise real-time fracture forecasting.



a b

Figure 1 – Visualization of mathematical model: a - stress-strain relationship; b - fracture propagation over time

The AI-enhanced approach reduces energy consumption while maintaining drilling efficiency, making it a promising tool for automated drilling optimization.

Artificial intelligence provides a powerful framework for analyzing and optimizing rock destruction processes in drilling operations. By integrating AI with mathematical models of rock failure, drilling efficiency can be improved significantly. The proposed model offers real-time adaptability, enhanced predictive accuracy, and automated parameter optimization, making it a valuable advancement in drilling technology. Future research will focus on extending AI-driven approaches to multi-physics simulations and real-time decision-making systems for fully autonomous drilling operations.

References:

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