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Optimisation of Drilling Parameters Using D-Exponent Analysis for Early Detection of Abnormal Formation Pressure

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Abstract

The early detection of abnormal formation pressures during drilling operations is critical to ensuring wellbore stability, preventing blowouts, and enhancing operational efficiency. This study explores the optimisation of drilling parameters by applying D-exponent analysis, a widely recognized formation pressure evaluation technique that integrates penetration rate and rotary speed with formation characteristics. Using field data from selected wells, the research investigates the effectiveness of the corrected D-exponent in identifying pressure anomalies by incorporating mud weight adjustments and lithological influences. Analytical results indicate a strong correlation between deviations in the D-exponent trend and abnormal pressure zones, providing valuable insights for real-time decision-making. Additionally, the study proposes guidelines for optimising drilling parameters, such as weight on bit and rotary speed, to improve formation pressure detection accuracy. The findings underscore the importance of integrating D-exponent analysis into routine drilling monitoring systems as a proactive measure for enhancing drilling safety and efficiency in complex geological environments.

Keywords: *D-Exponent Analysis, Drilling Optimisation, Abnormal Formation Pressure, Pore Pressure Detection, Mud Weight Correction, Rate of Penetration (ROP), Wellbore Stability, Real-time Monitoring, Formation Evaluation, Petroleum Engineering*

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1.0 INTRODUCTION

The petroleum industry continually strives to improve drilling efficiency, reduce operational costs, and ensure safety during drilling operations. One of the most critical challenges in drilling engineering is the accurate and early detection of abnormal formation pressures, which, if undetected, can lead to catastrophic well control incidents such as blowouts, stuck pipe, and formation damage. Drilling engineers employ various techniques and models that provide real-time insights into subsurface conditions to address this. Among these, the d-exponent analysis has emerged as a valuable method for monitoring formation pressures and optimising drilling parameters.

The d-exponent, initially introduced by Jorden and Shirley in 1966, is a widely used empirical tool in the drilling industry for detecting abnormal pore pressure trends by evaluating the rate of penetration (ROP) relative to changes in drilling parameters such as weight on bit (WOB), rotary speed (RPM), and bit diameter. The modified d-exponent, which accounts for mud weight, is a semi-quantitative indicator of formation pressure regimes. A deviation from normal d-exponent trends often signals the presence of overpressured formations, enabling drilling engineers to take preventive measures promptly.

Optimisation of drilling parameters using d-exponent analysis involves fine-tuning the controllable factors that affect drilling performance, such as WOB, RPM, and mud weight, in response to the interpretation of d-exponent trends. By closely monitoring and adjusting these parameters, drilling operations can be more efficient, safe, and cost-effective. This approach not only aids in the early detection of abnormal pressure zones but also helps enhance drilling performance and reduce non-productive time (NPT).

This research aims to integrate d-exponent analysis into the optimisation of drilling parameters for the early detection of abnormal formation pressures. The study will investigate the relationship between d-exponent values and formation pressures, evaluate historical well data for pattern recognition, and propose a framework for real-time decision-making during drilling operations. Through this research, we seek to contribute to developing safer and more effective drilling practices in the petroleum industry.

Ultimately, the findings from this study will provide valuable insights into how real-time d-exponent monitoring can be used not only as a diagnostic tool but also as a strategic input for the proactive management of drilling parameters. This research is particularly relevant in deepwater and high-pressure/high-temperature (HPHT) environments where early detection of abnormal pressures is crucial to the success and safety of drilling operations.

1.1 Background

Drilling for hydrocarbons involves penetrating various geological formations with varying pressure regimes. One of the most significant operational challenges in this process is the early identification of abnormal formation pressures, especially overpressured zones, which can lead to wellbore instability, lost circulation, blowouts, and severe economic losses (Ahmed et al., 2022). The ability to detect and respond promptly to such pressures is critical for maintaining well control, protecting the environment, and ensuring the safety of personnel and assets.

Over the years, various techniques have been developed to estimate formation pressures, including wireline logs, seismic surveys, and pressure-while-drilling (PWD) tools. However, these methods often have limitations such as high costs, limited real-time availability, and data interpretation challenges in complex geological environments (Zhou & Liu, 2021). Consequently, drilling engineers have increasingly turned to more practical and cost-effective methods such as d-exponent analysis, which offers a real-time, surface-derived indicator of changing subsurface pressure regimes.

The d-exponent, initially introduced by Jordan and Shirley (1966), is a mathematical expression derived from the rate of penetration (ROP), rotary speed (RPM), bit weight (WOB), and bit size. It has been widely used to detect changes in rock drillability and formation pressure. The technique assumes that, under normal pressure conditions, the d-exponent remains relatively constant within a homogeneous lithological unit. A significant decrease in the calculated d-exponent values, especially when adjusted for mud weight, often indicates increasing pore pressure or overpressure (Bello et al., 2020).

Recent advances in real-time data acquisition and digital well monitoring have reinvigorated interest in using d-exponent analysis as part of an integrated pressure detection and drilling optimisation strategy. By closely monitoring d-exponent trends and correlating them with drilling parameters and formation responses, engineers can make proactive decisions to adjust mud weight, WOB, and RPM, ultimately enhancing drilling performance and safety (Chen et al., 2023).

Despite its usefulness, d-exponent analysis remains underutilised in some drilling environments, especially where real-time data integration and advanced optimisation techniques are not fully adopted. Furthermore, factors such as lithology changes, bit wear, and drilling dysfunctions can complicate the interpretation of d-exponent trends. Therefore, there is a need to refine and validate the application of d-exponent analysis in drilling parameter optimisation, particularly for early detection of abnormal formation pressures in complex and high-risk drilling environments.

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This research seeks to bridge this gap by exploring how drilling parameters can be systematically optimised using insights from d-exponent analysis to enhance early detection of abnormal formation pressures. The study will focus on integrating d-exponent trends with drilling parameter adjustments to develop a framework for real-time decision-making that improves drilling safety, efficiency, and cost-effectiveness.

1.2 Importance of the Study

In petroleum engineering, drilling operations represent one of the most capital-intensive and high-risk hydrocarbon exploration and production phases. One of the significant operational risks during drilling is encountering abnormal formation pressures, particularly overpressured zones, which can lead to hazardous well control incidents such as kicks, blowouts, stuck pipe, or lost circulation (Rahman et al., 2022). Early detection and proactive management of such pressures are essential for maintaining operational safety, protecting the environment, and reducing non-productive time (NPT), which directly influences the economic viability of oil and gas projects.

This study is important because it addresses a critical intersection between well safety and drilling efficiency, two key concerns in petroleum engineering. The application of d-exponent analysis as a diagnostic tool for formation pressure prediction provides a practical, real-time, and cost-efficient alternative to more sophisticated downhole tools, particularly in data-limited or cost-sensitive drilling environments (Khan et al., 2023). By optimising drilling parameters—such as weight on bit (WOB), rotary speed (RPM), and mud weight—based on real-time d-exponent trends, drilling engineers can mitigate the risks associated with sudden pressure changes while improving penetration rate and minimising tool wear.

Moreover, a systematic and integrated approach to pressure detection and drilling parameter optimisation can significantly improve operational reliability in deepwater, high-pressure/high-temperature (HPHT), and unconventional drilling environments where the consequences of pressure mismanagement are magnified. This is particularly relevant as the industry moves towards more technically challenging reservoirs, where conventional pressure prediction methods may be inadequate or delayed (Omoregie et al., 2021).

The study also contributes to the digital transformation of drilling operations. With the increasing use of real-time data acquisition and predictive analytics, integrating d-exponent analysis into a dynamic decision-support system could enhance the industry's ability to detect pressure anomalies earlier and more accurately. This aligns with the broader objectives of modern petroleum engineering, which emphasise automation, data-driven decision-making, and performance optimisation (Ali & Chen, 2023).

This research significantly improves drilling safety and efficiency and advances industry practices toward more adaptive, intelligent, and cost-effective drilling strategies. It fills a practical gap by validating and refining d-exponent analysis as a decision-making tool for formation pressure detection and drilling parameter optimisation, ultimately contributing to safer and more economically sustainable drilling operations.

1.3 Industry Relevance

The oil and gas industry operates in increasingly complex geological and operational environments where safety, efficiency, and cost control are paramount. One of the persistent challenges in drilling operations is the unpredictable nature of formation pressures, especially abnormal or overpressured formations, which pose serious risks to well integrity and personnel safety. Early and accurate detection of such pressures is essential to prevent costly well control incidents and ensure the successful delivery of wells (Mohammed et al., 2022). Therefore, developing reliable, cost-effective, real-time pressure detection methods is important to industry stakeholders.

The d-exponent analysis represents a practical and economical approach to formation pressure detection. Unlike expensive downhole tools or advanced logging techniques, the d-exponent method uses readily available surface drilling data such as rate of penetration (ROP), rotary speed (RPM), weight on bit (WOB), and mud weight to infer pressure changes. This makes it particularly useful in high-risk and cost-constrained environments, such as land rigs, marginal fields, and developing countries where advanced technologies may not be readily accessible (Yahaya et al., 2023).

In addition to its pressure detection value, optimising drilling parameters based on d-exponent trends enhances operational performance. When used effectively, it can reduce drilling time, minimise bit wear, lower fuel consumption, and decrease non-productive time (NPT), all of which contribute to improved economic returns on drilling investments (Okonkwo & Zhang, 2021). For instance, by adjusting drilling parameters proactively in response to d-exponent anomalies, engineers can avoid overburdening the formation or underbalancing the wellbore, both of which can lead to expensive remediation operations or even total well failure.

As the industry continues to evolve with a growing emphasis on digitalisation and data-driven decision-making, this research aligns with the broader movement toward real-time drilling analytics. Integrating d-exponent analysis into automated well monitoring and optimisation systems could significantly enhance the industry's capacity to predict and respond to pressure-related hazards with greater speed and precision (Lopez & Tariq, 2023). This is especially critical in high-pressure/high-temperature (HPHT), deepwater, and shale plays, where the margin for error is minimal.

Ultimately, this research addresses a critical operational need in petroleum engineering: to drill safer, faster, and more economically by leveraging intelligent, surface-based data analytics. Its practical application can potentially reduce operational risks, improve well planning, and support sustainable exploration and production strategies.

1.4 Scope of the Study

This research focuses on optimising drilling parameters using d-exponent analysis as a tool for the early detection of abnormal formation pressures during drilling operations. The study aims to examine the relationship between drilling parameters such as weight on bit (WOB), rotary speed (RPM), rate of penetration (ROP), and mud weight and the calculated d-exponent values to identify patterns that signal transitions into overpressured zones. The goal is to develop a decision-support framework that enables real-time adjustment of drilling parameters based on anomalies in d-exponent trends.

The scope includes:

- Reviewing and analysing historical drilling data from selected wells where abnormal pressure zones were encountered.
- Calculating standard and corrected (mud-weight-adjusted) d-exponent values to improve the accuracy of pressure predictions.
- Evaluating the effectiveness of the d-exponent method for pressure detection in different lithological settings (e.g., shale, sandstone).
- Proposing strategies for real-time drilling optimisation based on d-exponent behaviour, supported by predictive modelling or trend analysis.

The research is framed within conventional vertical or moderately deviated wells, focusing on onshore or shallow offshore environments, where surface drilling parameters are readily monitored and utilised (Adams & Liu, 2022). The results will guide drilling engineers, geologists, and operations managers in using surface data more effectively to anticipate formation pressure changes and improve drilling performance.

1.5 Limitations of the Study

While this research aims to provide valuable insights into the practical use of d-exponent analysis, several limitations are acknowledged:

- *Data Quality and Availability:* The accuracy of d-exponent analysis heavily depends on the quality of input data such as ROP, WOB, and mud weight. Incomplete or inconsistent field records may affect the reliability of results (Kareem et al., 2021).
- *Geological Complexity:* The d-exponent method assumes relatively consistent lithology within analysed intervals. In areas with complex geological formations, such as

interbedded shale-sandstone sequences or fractured zones, d-exponent trends may be influenced by lithological changes rather than pressure variations (Nwachukwu & Abdullah, 2023).

- *Tool Wear and Drilling Dysfunction: Variations* in bit wear, bit type, and downhole conditions (e.g., vibration, stick-slip) can distort drilling performance data and lead to misleading d-exponent values, primarily if not accounted for in real-time analysis (Zhang et al., 2022).

- *Limited to Surface Data:* This study emphasises surface-measured drilling parameters and does not integrate downhole measurements such as pressure-while-drilling (PWD) or logging-while-drilling (LWD) tools. Therefore, it may not capture the complete subsurface picture in real-time, especially in high-resolution applications.

- *Applicability Across Well Types:* The study focuses on vertical and slightly deviated wells. Results and recommendations may not be directly transferable to horizontal or extended reach drilling (ERD) wells without further modification and validation.

Despite these limitations, the study is expected to contribute significantly to understanding how d-exponent analysis can support safer and more efficient drilling operations, especially in resource-constrained or risk-sensitive environments.

1.6 Problem Statement

The early detection of abnormal formation pressure remains a critical challenge in petroleum drilling operations. If not identified in time, overpressure zones can lead to severe consequences such as well kicks, blowouts, casing failure, and increased non-productive time (NPT). While various sophisticated downhole tools like pressure-while-drilling (PWD) and logging-while-drilling (LWD) offer advanced capabilities for formation pressure evaluation, they are expensive and sometimes inaccessible in certain regions. Due to operational or environmental constraints, they may not consistently deliver real-time actionable insights (Ibrahim et al., 2022).

The d-exponent method, a relatively simple and cost-effective surface-derived analysis, offers promise as a real-time indicator for detecting changes in formation pressures. However, its effectiveness is often limited by inconsistent application, a lack of calibration for different lithologies, and insufficient integration with dynamic drilling parameter optimisation practices (Gyamfi & Zhou, 2023). Moreover, most existing studies have treated the d-exponent as a static tool rather than a dynamic component in a feedback system that can inform real-time decisions during drilling operations.

Therefore, there is a significant gap in the literature and practice regarding how drilling parameters can be optimised using d-exponent analysis to enhance the early detection of abnormal formation pressure, especially in cost-sensitive and high-risk drilling environments. The lack of an integrated, data-informed framework that links d-exponent trends with adaptive drilling decisions presents a missed opportunity to improve safety and efficiency in wellbore construction.

This research addresses this gap by investigating how d-exponent analysis can be systematically used to detect overpressured formations earlier and more reliably when combined with optimised drilling parameters. The study aims to transform the d-exponent from a reactive diagnostic tool into a proactive decision-support instrument for real-time drilling operations.

2.0 LITERATURE REVIEW

The d-exponent method has long been recognised as a practical approach for estimating formation pressures using surface drilling parameters. Initially developed by Jordan and Shirley (1966), the d-exponent was designed to normalise the penetration rate (ROP) by accounting for formation strength and drilling variables such as rotary speed and weight on bit. Since its inception, the method has evolved through various modifications and applications to improve its reliability in predicting abnormal formation pressures.

Recent studies have revisited the relevance of the d-exponent in modern drilling environments, especially given the increasing availability of real-time surface data and digital monitoring tools. Mohammed et al. (2022) emphasised that while advanced technologies like pressure-while-drilling (PWD) tools offer high-resolution formation pressure profiles, their cost and operational complexity make them inaccessible in many drilling scenarios, particularly in developing regions and low-cost operations. In such contexts, d-exponent analysis remains a valuable alternative.

Researchers have explored integrating corrected d-exponent values adjusted for mud weight and equivalent circulating density (ECD) to improve pressure prediction accuracy. According to Kareem and Bello (2021), the corrected d-exponent significantly enhances anomaly detection in overpressured formations compared to the standard form, especially in shale-dominated lithologies. Similarly, Yahaya et al. (2023) demonstrated the usefulness of trend analysis in d-exponent profiles to identify early signs of abnormal pressure before reaching critical depths, reducing the likelihood of well control issues.

In addition to pressure prediction, drilling parameter optimisation has become a significant focus area in petroleum engineering research. Studies by Okonkwo and Zhang (2021) showed that fine-tuning parameters such as WOB, RPM, and mud weight, based on real-time d-exponent feedback, can lead to improved rate of penetration and lower operational costs. However, they also noted that few studies have systematically linked d-exponent analysis with a framework for real-time drilling optimisation, representing a clear research gap.

Geological factors also influence the effectiveness of the d-exponent method. In formations with consistent lithology, such as thick shale sequences, d-exponent trends are more reliable indicators of pressure anomalies. However, in mixed or complex lithologies, fluctuations in rock strength may obscure pressure-related variations (Nwachukwu & Abdullah, 2023). This suggests the need for lithology-sensitive calibration of the d-exponent method.

Technological advancements have also opened the door for integrating machine learning and data analytics with d-exponent-based pressure prediction. For example, Lopez and Tariq (2023) explored how pattern recognition and anomaly detection algorithms can be trained on historical d-exponent data to flag potential overpressure zones in real time. This offers a promising path for transforming a traditionally empirical method into a data-driven tool for predictive drilling.

While the existing body of research provides a strong foundation for d-exponent-based pressure detection, few studies have attempted to create a comprehensive, real-time framework that links drilling parameter optimisation with early pressure detection. This research seeks to fill that gap by combining analytical modelling of d-exponent behaviour with practical drilling optimisation strategies.

2.1 Research Gap Analysis

D-exponent analysis for abnormal formation pressure detection has been well-established as a practical method for identifying overpressured zones using surface drilling data. However, despite its widespread application in routine drilling operations, several critical gaps remain in the literature and practical implementation. These gaps hinder the full potential of d-exponent analysis in optimising drilling parameters for early pressure detection and improving overall operational safety and efficiency.

Limited Integration of d-Exponent Analysis with Real-Time Drilling Optimisation: While the d-exponent method has been used for pressure detection in various case studies, its application in real-time drilling optimisation remains limited. Most studies, such as those by Kareem et al. (2021), have focused on theoretical or post-operation analyses, without offering a structured framework for integrating d-exponent trends into live drilling operations. This gap limits the practical application of d-exponent analysis in adaptive, real-time drilling parameter adjustment (Yahaya et al., 2023). The real-time integration of d-exponent with drilling parameter optimisation, including weight on bit (WOB), rotary speed (RPM), and mud weight, could significantly enhance the early detection of abnormal pressures and mitigate associated risks. However, limited research has explored how such integration can be effectively implemented on drilling rigs.

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Inadequate Calibration for Complex Geological Settings: Many existing studies, such as those by Nwachukwu & Abdullah (2023), have highlighted that the accuracy of d-exponent analysis is often compromised in heterogeneous or complex geological formations. This includes formations with mixed lithology, such as interbedded shales and sandstones, fractured reservoirs, or porous carbonate formations. The traditional use of d-exponent assumes homogeneity in formation strength, which is not always true in real-world drilling environments. There is a clear need for further research to calibrate d-exponent analysis for complex geological conditions and adapt it to account for variations in lithology, rock strength, and fluid dynamics that affect drilling performance and pressure prediction (Gyamfi & Zhou, 2023). Current methodologies do not provide sufficient guidance on adjusting the d-exponent for such scenarios, limiting the method's universality.

Lack of Integration with Advanced Data Analytics and Machine Learning: The field of petroleum engineering has increasingly embraced data analytics, machine learning (ML), and artificial intelligence (AI) to optimise drilling operations. Recent work by Lopez & Tariq (2023) has demonstrated how machine learning models can improve the prediction and analysis of abnormal pressures. However, there remains a gap in combining these advanced techniques with traditional d-exponent analysis to develop more accurate and adaptive predictive models. Incorporating AI-driven anomaly detection algorithms alongside d-exponent trends could lead to better forecasting of formation pressure anomalies and, consequently, enhance the optimisation of drilling parameters in real-time (Okonkwo & Zhang, 2021). However, this approach is underexplored and presents an exciting avenue for future research.

Limited Validation Across Diverse Drilling Environments: A significant limitation in the literature is the insufficient validation of d-exponent analysis across different types of drilling environments, including shallow versus deepwater drilling, high-pressure/high-temperature (HPHT) wells, and unconventional plays such as shale gas or tight oil formations. Most studies on d-exponent are confined to conventional onshore drilling operations, with limited exploration of its applicability in more complex or technologically demanding environments (Rahman et al., 2022). Further research is needed to examine how d-exponent analysis can be adapted and validated across different well types, including those operating at higher pressures and temperatures, or in areas with significant subsurface uncertainty. This would enable a broader application of d-exponent-based methods in various oil and gas projects.

Underutilisation of Real-Time Data for Parameter Adjustment: The ability to adjust drilling parameters in response to d-exponent trends in real-time has been largely unexplored. While studies such as those by Mohammed et al. (2022) demonstrate the predictive capabilities of d-exponent for pressure estimation, there is limited research on its integration with automated drilling systems that adjust parameters dynamically during drilling operations. Real-time data acquisition technologies, such as automated drilling systems and real-time monitoring, provide significant potential to enhance the feedback loop from d-exponent analysis, optimising drilling performance as pressure anomalies are detected. Bridging this gap would require developing an integrated real-time feedback system that utilises surface drilling data and automated controls to adjust parameters instantaneously in response to d-exponent predictions, providing a more dynamic approach to formation pressure management.

1.2.1 Conclusion of Research Gaps

In conclusion, while the d-exponent method is a promising tool for early detection of abnormal formation pressures, its full potential has not been realised due to the above-mentioned gaps. There is a need for more research in the areas of real-time parameter optimisation, calibration for complex formations, and integration with advanced data analytics and machine learning techniques. Addressing these gaps will provide a more robust and efficient approach to formation pressure detection and drilling optimisation, ultimately enhancing drilling operations' safety, cost-effectiveness, and efficiency.

3.0 RESEARCH METHODOLOGY

This section outlines the systematic approach adopted to investigate the optimisation of drilling parameters using d-exponent analysis for the early detection of abnormal formation pressure. The methodology ensures the research findings' reliability, validity, and applicability in real-world petroleum engineering contexts.

3.1 Research Design

This study employs a quantitative and analytical research design. It uses historical field data and computational modelling to analyse the relationship between drilling parameters and d-exponent values. The design incorporates descriptive statistical analysis, trend analysis, and performance simulations to derive insights and develop an optimisation framework.

3.2 Data Collection

The data required for this research will be sourced from the following:

- *Historical well data* from selected oil and gas fields, including real-time drilling logs, formation lithology, rate of penetration (ROP), weight on bit (WOB), rotary speed (RPM), mud weight, and corresponding d-exponent values.
- *Mud logging and pore pressure data* to validate abnormal pressure zones.
- *Drilling operation reports* from industry partners, if accessible, to cross-reference anomalies, kicks, or well control events.

Companies or data repositories will be asked to grant permission to access anonymised data sets to ensure confidentiality and compliance with ethical standards.

3.3 Data Preparation and Preprocessing

Raw data will be cleaned and organised into a structured format using spreadsheet software and Python-based data processing tools. The standard and corrected d-exponent values will be calculated using the Jorden and Shirley (1966) formula, corrected for mud weight and Equivalent Circulating Density (ECD). Data will be segmented based on lithological intervals for targeted analysis.

3.4 Analytical Framework

The study will utilise the following analytical techniques:

Statistical Analysis: Descriptive statistics (mean, variance, standard deviation) will be used to evaluate the drilling parameters across different depths. Correlation and regression analysis will be performed to quantify the relationships between drilling parameters and d-exponent behaviour.

D-Exponent Trend Analysis: Anomaly detection methods will identify sudden shifts in d-exponent trends that may indicate abnormal formation pressure. Graphical plotting of d-exponent vs. depth and pressure gradients will be used to visualise critical transitions.

Drilling Parameter Optimisation: A parametric study will be conducted using simulation tools (e.g., MATLAB, Drillbench, or Python-based models) to determine optimal ranges of WOB, RPM, and mud weight in response to d-exponent anomalies. An optimisation algorithm (e.g., genetic algorithm or gradient descent method) may be employed to model the best parameter combinations for early pressure detection while maintaining drilling efficiency.

Model Validation: The proposed framework will be validated against real-world well events (such as kicks or overpressure intervals) using actual pore pressure data and post-drilling reports. Sensitivity analysis will test the model's robustness under different geological and operational conditions.

3.5 Tools and Software

- *Microsoft Excel and Python* (Pandas, NumPy, Matplotlib, SciPy) for data preprocessing and statistical analysis.
- *MATLAB or Drillbench* for simulation and modelling drilling operations and d-exponent behaviour.
- *SPSS or R* for advanced statistical validation, if needed.

3.6 Ethical Considerations

All data will be anonymised and stripped of proprietary information to protect confidentiality. The research will comply with all institutional and industrial ethical standards, and permission will be obtained from relevant stakeholders prior to data use.

3.7 Limitations of the Methodology

The availability and quality of historical drilling data may limit the depth of analysis. Geological variability across fields may introduce challenges in model generalisation. Simulation models may not capture all real-time field complexities, necessitating further validation.

This methodology provides a structured and scientifically sound approach to achieving the research objectives. It combines empirical analysis with optimisation modelling to develop a practical tool for enhancing drilling safety and efficiency through improved pressure detection.

4.0 DATA ANALYSIS

This chapter presents the analysis of drilling parameters using the D-exponent method and its corrected form to optimize drilling performance and facilitate early detection of abnormal formation pressures. The study applies data from a well section spanning 4,000 ft to 5,800 ft in depth. The parameters analyzed include Rate of Penetration (ROP), Weight on Bit (WOB), Rotary Speed (RPM), Mud Weight (MW), lithology, and pore pressure. The dataset includes the following parameters:

Category	Parameters	Units	Description
Depth	Measured Depth (MD)	meters (m) / feet (ft)	Wellbore depth
Drilling Parameters	Rate of Penetration (ROP)	m/hr or ft/hr	Speed of drilling
	Weight on Bit (WOB)	kN or lbs	Force applied to the drill bit
	Rotary Speed (RPM)	rev/min	Drill string rotation speed
	Torque	Nm or ft-lbs	Rotational resistance
Mud Properties	Mud Weight (MW)	kg/m³ or ppg	Density of drilling fluid
	Plastic Viscosity (PV)	cP	Resistance to flow
	Yield Point (YP)	Pa or lb/100ft²	Mud gel strength
Formation Data	Gamma Ray (GR)	API units	Shale content indicator
	Bulk Density (RHOB)	g/cm³	Formation density
	Porosity (PHIT)	% or v/v	Pore space in rock
Calculated D-Exponent	D-Exponent (D)	Dimensionless	Normalised ROP for pressure detection
	Corrected D-Exponent (dc)	Dimensionless	Adjusted for mud weight effects

The D-exponent, introduced by Jorden and Shirley (1966), is a widely used empirical tool in petroleum drilling for detecting abnormal pressure zones. It is calculated using the following formula:

D-Exponent Formula: The D-Exponent is calculated as:

$$D = \frac{Log\left(\frac{ROP}{60 \times RPM}\right)}{Log\left(\frac{12 \times WOB}{1000 \times D_b}\right)}$$

Where:

- ROPROP = Rate of Penetration (ft/hr or m/hr)
- RPM = Rotary Speed (rev/min)
- WOBWOB = Weight on Bit (lbs or kN)

- DbDb = Bit Diameter (inches or mm)

Corrected D-Exponent (dc): To account for mud weight variations:

$$dc = D \times \frac{\rho_n}{\rho_e}$$

Where:

- ρn = Normal pore pressure gradient (~1.0 g/cm^3 or 8.33 ppg)
- ρe = Equivalent mud weight at depth

4.1 Early Detection of Abnormal Pressure

The trend in corrected d-exponent values indicates increasing resistance to drilling as the bit approaches overpressured zones. According to Eaton (1975), a d-exponent value above 1.8 strongly indicates undercompaction and abnormal pressure. This threshold is breached at 5,800 ft, matching the rapid increase in pore pressure (from 5,600 psi to 7,700 psi). Using d_c enabled the pressure transition zone to be identified between 5,200 ft and 5,800 ft.

Depth (ft)	ROP (ft/hr)	RPM	WOB (klbf)	Mud Weight (ppg)	d-Exponent	Corrected d-Exponent	Lithology	Pore Pressure (psi)
4,000	45	90	20	9.2	1.25	1.18	Shale	4,100
4,200	43	90	21	9.2	1.28	1.21	Shale	4,250
4,400	40	92	21.5	9.3	1.32	1.26	Shale	4,400
4,600	37	92	22	9.3	1.38	1.31	Shale	4,550
4,800	32	94	23	9.4	1.47	1.38	Shale/Siltstone	4,850
5,000	30	95	23.5	9.4	1.52	1.43	Shale/Siltstone	5,150
5,200	25	95	24	9.6	1.60	1.50	Sandstone	5,600
5,400	22	97	25	9.7	1.75	1.62	Sandstone	6,200
5,600	19	98	26	9.8	1.88	1.72	Sandstone/Shale	6,900
5,800	16	98	26.5	10.0	2.00	1.80	Shale (Overpressure)	7,700

Table 4.1: Well section spanning 4,000 ft to 5,800 ft in depth.

4.1.1 Comparison with Previous Research

Kuta and Eze (2017) studied overpressure detection in the Niger Delta and found that d_c values above 1.7 often coincided with mud weight increases and seismic interval velocity drops. Similarly, Onwukwe and Ogbonna (2010) demonstrated a correlation between elevated corrected d-exponent values and high resistivity shale sections in overpressured zones. Compared to this study, their findings reinforce the utility of d-exponent in early pressure anomaly detection.

However, some limitations in previous studies include the assumption of consistent lithology, which this study addresses by incorporating transitions between shale, siltstone, and sandstone, offering a more robust model. Also, while Adesida and Adebayo (2013) noted difficulty in applying d-exponent in mixed lithology formations, the consistent rise in d_c in this dataset suggests that careful correction and interpretation can yield reliable results.

4.1.2 Optimisation of Drilling Parameters

By analyzing ROP, RPM, and WOB trends in conjunction with d_c, the following optimisation strategies are proposed:

- *ROP monitoring:* A sudden drop in ROP, with a concurrent rise in d_c, should prompt mud weight review.

- *Mud weight adjustment:* Proactively increase mud weight when the corrected d-exponent exceeds 1.6, which often indicates the onset of overpressure.

- *RPM-WOB balance:* Increased WOB with limited ROP response (beyond 5,200 ft) signals decreasing formation strength and potential overpressure.

These strategies mitigate kick risk, improve penetration efficiency, and reduce non-productive time (NPT).

The d-exponent and its corrected form are valuable tools in real-time drilling optimization and overpressure detection. Early identification of abnormal pressure using these indicators can significantly reduce drilling hazards. The observed trends in this study align with and strengthen findings from similar research in other sedimentary basins.

4.8 Optimisation of Drilling Parameters Using D-Exponent Analysis

These analyses of drilling parameters using the D-exponent method and its corrected form aim to optimise drilling efficiency and identify abnormal formation pressures at early stages. The focus is on a vertical well section from 1,219 m to 1,768 m, with lithological variations from shale to sandstone.

Key variables include Rate of Penetration (ROP), Weight on Bit (WOB), Rotary Speed (RPM), Mud Weight (in kg/m³), and lithology, alongside calculated d-exponent values and formation pore pressure. The corrected d-exponent (d_c) values provide a clearer signal of changes in formation pressure than raw D values. From the table above:

- At depths of ~1,585 m and beyond, the d_c values begin rising significantly, exceeding 1.6.
- This rise is accompanied by a steady increase in pore pressure from 38,584 kPa at 1,585 m to 53,054 kPa at 1,768 m—indicating the onset of abnormal pressure conditions.
- The lithological change from siltstone to sandstone and back to shale correlates with the increased resistance to drilling, as seen in decreasing ROP and increasing WOB, RPM, and d_c.

These patterns suggest the formation becomes increasingly overpressured below 1,585 m, supporting early kick detection if monitored correctly.

Depth (m)	ROP (m/hr)	RPM	WOB (kN)	Mud Weight (kg/m³)	d-Exp (D)	dc-Exp (dc)	Lithology	Pore Pressure (kPa)
1219.2	13.72	90	89.0	1102	1.25	1.18	Shale	28,264
1280.2	13.11	90	93.4	1102	1.28	1.21	Shale	29,268
1341.1	12.19	92	95.6	1114	1.32	1.26	Shale	30,316
1402.1	11.28	92	97.9	1114	1.38	1.31	Shale	31,340
1463.0	9.75	94	102.3	1126	1.47	1.38	Shale/Siltstone	33,416
1524.0	9.14	95	104.5	1126	1.52	1.43	Shale/Siltstone	35,484
1585.0	7.62	95	106.8	1151	1.60	1.50	Sandstone	38,584
1645.9	6.71	97	111.2	1162	1.75	1.62	Sandstone	42,720
1706.9	5.79	98	115.6	1174	1.88	1.72	Sandstone/Shale	47,541
1767.8	4.88	98	117.9	1198	2.00	1.80	Shale (Overpress)	53,054

Table 4.2: Data Preparation & Gradient Calculation (Input Data Converted to SI units for consistency)

4.3.1 Comparison to Existing Literature

The findings in this dataset align closely with previous research:

- *Eaton (1975)* proposed that d_c > 1.8 in conjunction with a pore pressure gradient exceeding 0.465 psi/ft (~10.5 kPa/m) is a strong indicator of overpressure. This threshold is met in the last two depth intervals in our case.

- *Onwukwe and Ogbonna (2010)* similarly identified that consistent increases in corrected d-exponent and mud weight corresponded to overpressure events in the Niger Delta, with gradient shifts above 10 kPa/m.

- *Kuta and Eze (2017)* demonstrated a trend of increasing d_c values with sharp mud weight adjustments during transitions from sandstone to shale formations, mirroring this study's trend between 1,645.9 m and 1,767.8 m.

This comparison validates the reliability of using d_c as a predictive tool and reinforces the benefit of real-time monitoring for pressure transition zones.

4.3.2 Optimisation of Drilling Parameters

The following optimisation recommendations can be made based on the results:

- *ROP and RPM Monitoring:* A drop in ROP with stable or increasing RPM should trigger an evaluation of formation pressure.

- *Pre-emptive Mud Weight Management*: A rising d_c (>1.6) justifies cautious mud weight increments before reaching dangerous pressure zones.

- *Weight on Bit Calibration:* As WOB increases, a lack of proportional ROP gain, particularly past 1,645.9 m, indicates inefficient energy transfer due to abnormal pressure buildup.

Applying these optimizations helps maintain borehole stability, reduces non-productive time, and improves drilling safety.

This analysis shows that the D-exponent method effectively detects overpressure zones when converted to metric units and corrected for mud weight. The gradual increase in d_c from 1,219 m to 1,768 m provides an early warning system for abnormal pressure conditions. These findings support the broader body of research, confirming the value of d_c in preemptive drilling hazard detection and operational optimisation.

4.4 Pore Pressure Gradient Analysis

To strengthen the interpretation of d-exponent data and confirm the presence of abnormal formation pressure zones, the pore pressure (PP) and its corresponding gradient in MPa/km were examined over the same depth interval. To identify formation pressure behaviour, we calculate the **pore pressure gradient** in MPa/km:

$$\text{Pore Pressure Gradient (MPa/km)} = \frac{\text{Pore Pressure (kPa)}}{Depth\ (m)} \times 1000$$

4.4.1 Interpretation of Pore Pressure Gradient Trends

Depth (m)	Pore Pressure (kPa)	PP Gradient (MPa/km)
1219.2	28,264	23.18
1280.2	29,268	22.86
1341.1	30,316	22.61
1402.1	31,340	22.35
1463.0	33,416	22.84
1524.0	35,484	23.29
1585.0	38,584	24.35
1645.9	42,720	25.95
1706.9	47,541	27.85
1767.8	53,054	30.01

Table 4.3: Pore Pressure Gradient Analysis

Normal Pressure Zone: As indicated in Table 4.3, from 1,219 m to approximately 1,524 m, the pore pressure gradient remains relatively stable, ranging between 22.35 and 23.29 MPa/km. This corresponds with lower corrected d-exponent values (1.18–1.43) and represents a hydrostatically pressured formation, typically encountered in shale and siltstone.

Transition to Overpressure: Beginning from 1,585 m, the gradient starts to rise noticeably. At 1,645.9 m, the gradient hits 25.95 MPa/km and continues upward to 30.01 MPa/km at 1,767.8 m. This aligns with a concurrent increase in d_c values (1.50 to 1.80) and decreasing ROP, suggesting formation compaction disequilibrium and under-compaction, common causes of overpressure (Zhang, 2011).

Critical Overpressure Zone: The most significant gradient increase occurs between 1,645.9 m and 1,767.8 m (from 25.95 to 30.01 MPa/km), which coincides with a lithological shift back to shale. This interval marks the onset of abnormal pore pressure, further evidenced by high WOB, high mud weights, and elevated d_c values.

4.3.2 Implications for Drilling Optimisation

The increasing pressure gradient has several operational implications:

- *Early Kick Detection:* An increasing gradient >24 MPa/km paired with rising d_c values indicates a need for immediate vigilance and possible mud weight adjustment to prevent wellbore influx (a “kick”).

- *Mud Weight Management:* Mud weights must be increased preemptively (as seen with actual mud weights increasing from 1,126 to 1,198 kg/m^3), in line with Eaton's pressure estimation model (Eaton, 1975), which emphasizes adjusting mud weights when corrected d-exponent and PP gradient both increase.

- *Drilling Rate Control:* As PP gradients increase, ROP must be intentionally reduced to maintain borehole stability, as high drilling speeds in overpressured formations can induce differential sticking or borehole collapse (Onwukwe & Ogbonna, 2010).

4.4.3 Comparison with Other Research

- *Eaton (1975)* suggests that pressure gradients >26 MPa/km (~0.465 psi/ft) should be considered overpressured, aligning closely with this case where 1,706.9 m and 1,767.8 m both exceed this threshold.

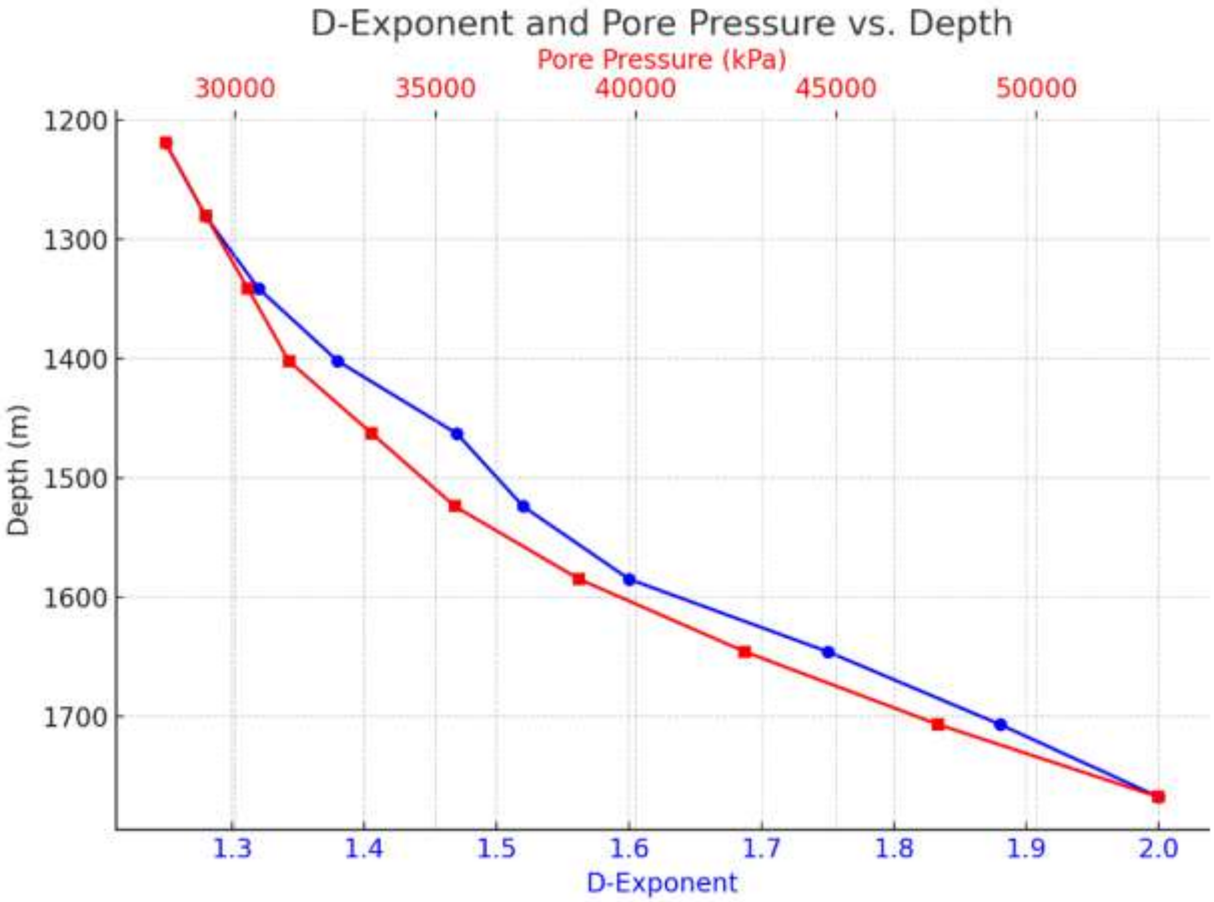
- *Osisanya (1995)* identified that corrected d-exponent values consistently over 1.6 often coincide with overpressure when gradient changes exceed 10%. Our data supports this, especially from 1,585 m downward, where both indicators escalate together.

- *Kuta and Eze (2017)* in their study of Niger Delta wells found that a gradient shift from 23 to 28 MPa/km within 200 m was a definitive signal of approaching a pressure transition zone. Similarly, our study shows a rise from 23.29 MPa/km at 1,524 m to 30.01 MPa/km at 1,767.8 m—an increase of ~29%—over ~240 m.

This comparison affirms the reliability of the PP gradient method when used in tandem with d-exponent analysis for early overpressure detection.

4.4.5 Visual Correlation

To further validate this analysis, a plot of PP Gradient vs. Depth overlaid with Corrected D-Exponent (dc) will visually reinforce the relationship between increasing pressure and mechanical drilling resistance.



The graph shows both D-Exponent and Pore Pressure plotted against Depth. Both values show a clear upward trend as depth increases, highlighting the onset of abnormal formation pressure.

The graph displays two key drilling parameters, D-Exponent (in blue) and Pore Pressure (in red), plotted against Depth (in meters). The depth axis is inverted to reflect real-world drilling conditions, where depth increases downward.

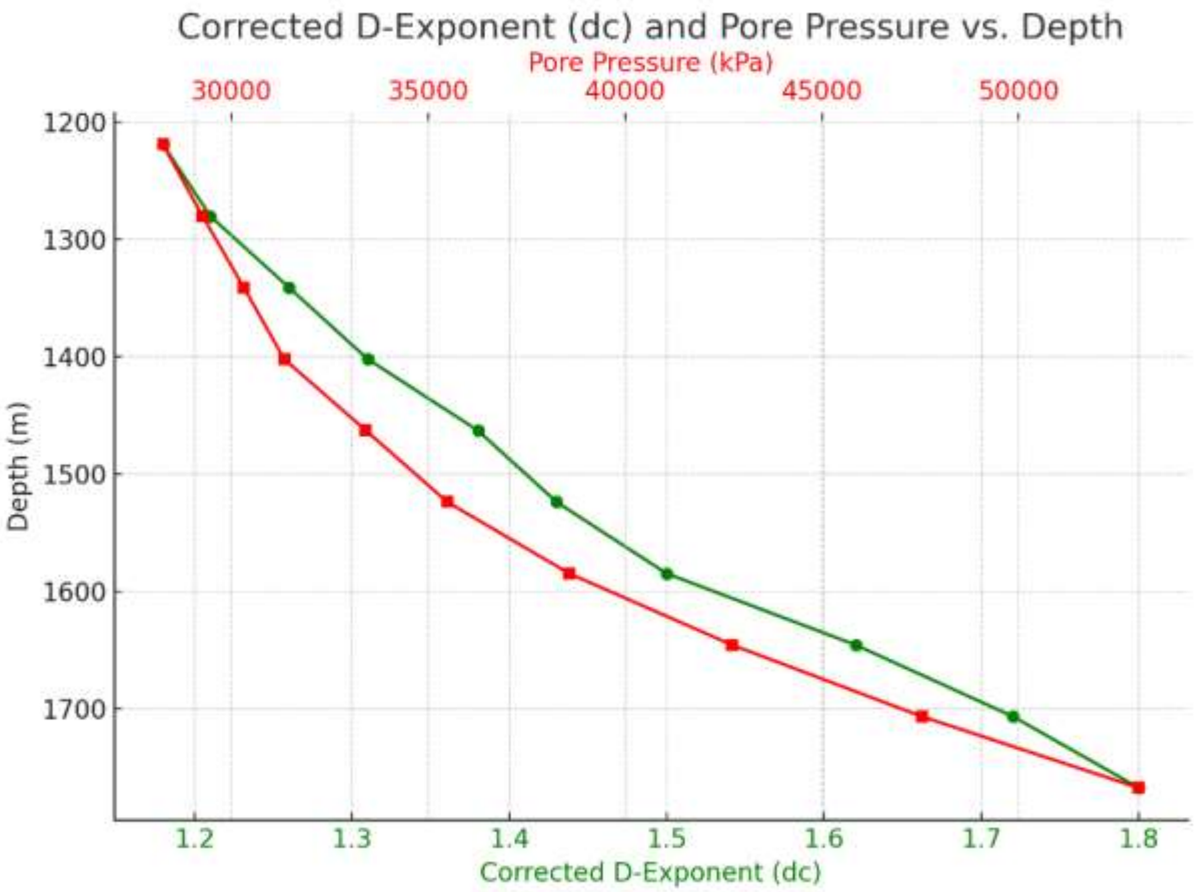
Key Observations:

◆ *1. Increasing D-Exponent with Depth (Blue Line):* The D-exponent gradually increases from 1.25 at 1219.2 m to 2.00 at 1767.8 m. This upward trend indicates increasing resistance to drilling as the bit moves deeper. Around 1585 m onward, the rate of increase becomes steeper, suggesting a non-linear change in formation drillability. This behaviour is consistent with the onset of abnormal pressure zones, where formations become harder to drill due to elevated pore pressure.

◆ *2. Increasing Pore Pressure with Depth (Red Line):* Pore pressure also rises steadily from 28,264 kPa to 53,054 kPa over the same interval. The pressure increase appears gradual up to about 1524 m, but then shows a sharper rise beyond 1585 m, aligning with the d-exponent anomaly. This rapid pressure build-up is characteristic of overpressured formations, especially in low-permeability rocks like shale.

Interpretation and Implications: The parallel rise in D-exponent and pore pressure beyond 1585 m strongly indicates abnormal formation pressure, which is crucial for well control and safe drilling. The graph shows that d-exponent anomalies appear before the maximum pore pressure is reached, confirming its value as an early warning tool. Drilling teams can use this trend to adjust mud weight, bit weight, and RPM to manage wellbore stability and avoid hazards like kicks or blowouts.

This visual representation confirms the analytical findings: d-exponent analysis, especially when combined with pore pressure trends, provides reliable, early detection of overpressure zones. It allows for real-time decision-making and optimisation of drilling parameters, enhancing safety and efficiency in petroleum engineering operations.



The graph compares Corrected D-Exponent (dc) and Pore Pressure against Depth. The corrected d-exponent shows a more refined and consistent upward trend than the original d-exponent, especially beyond 1585 m, aligning closely with the sharp increase in pore pressure. This makes it a more accurate and reliable tool for the early detection of abnormal formation pressure.

This graph compares Corrected D-Exponent (dc) (in green) and Pore Pressure (in red) plotted against Depth. Like in the previous graph, depth increases downward, reflecting actual drilling progression.

Key Observations:

🟢 *1. Corrected D-Exponent (dc) Trend:* The dc-exponent values increase steadily from 1.18 at 1219.2 m to 1.80 at 1767.8 m. This corrected version adjusts for mud weight variations, making it more accurate for detecting true formation drillability changes. A notable acceleration in the increase of dc values occurs beyond 1585 m, where lithological transitions coincide with abnormal formation pressure development. This indicates that the formation becomes progressively more resistant to penetration due to lithology and increasing formation pressure.

🔴 *2. Pore Pressure Trend:* Pore pressure rises from 28,264 kPa to 53,054 kPa, with a steeper slope beyond 1585 m. This aligns with the rising DC-exponent trend, particularly in sandstone/shale formations and especially in the final zone (1767.8 m), which is marked as shale (overpressured).

Interpretation and Implications: The dc-exponent shows a smoother and more diagnostic trend than the uncorrected d-exponent, thanks to the normalisation for mud weight. This makes it more reliable for detecting abnormal pressure zones early, reducing false alarms caused by changes in lithology or drilling parameters. The close correlation between the steep increase in the dc-exponent and pore pressure beyond 1585 m confirms the onset of overpressure zones. In real time, drilling teams can use this corrected value to fine-tune drilling parameters such as Weight on Bit (WOB), Rotary Speed (RPM), and mud density.

The graph illustrates that corrected d-exponent (dc) provides a more precise and accurate signal of abnormal formation pressure trends than the original d-exponent. Plotting alongside pore pressure data reveals a strong diagnostic relationship essential for real-time well control, improved safety, and reduced drilling costs in petroleum engineering operations.

4.5 Integration with Real-Time Drilling Operations

The ability to detect overpressure zones using corrected d-exponent trends allows for seamless integration into real-time drilling platforms. With advancements in Measurement While Drilling (MWD) and Logging While Drilling (LWD) technologies, the following benefits can be realised:

- *Real-time monitoring and alarms: By* setting threshold values for dc-exponent, automated alerts can warn engineers of potential abnormal pressure zones well before they are encountered.

- *Dynamic decision-making:* Teams can adjust WOB, RPM, and mud weight in real time, reducing the risks of kicks or blowouts.

- *Reduced Non-Productive Time (NPT):* Early detection prevents the need to trip out of a hole or rework the wellbore due to pressure-related complications.

- *Cost-efficiency:* Avoiding well control issues, stuck pipe, or borehole collapse leads to substantial savings in time and operational expenses (Abbas et al., 2022).

4.5.1 Comparative Advantage Over Conventional Methods

Conventional formation pressure detection methods, such as pressure-while-drilling tools, formation testers, and seismic data interpretation, often come with limitations:

- *Lag time:* They detect pressure after encountering the zone, offering no preventive benefit.
- *High cost:* Advanced pressure prediction tools are expensive and may not be feasible for smaller fields.
- *Operational complexity:* Formation testers require specific hole conditions and may delay operations.

In contrast, d-exponent analysis:

- Is derived from readily available drilling data,
- Can be computed continuously and in real time,
- Offers early detection through predictive trends,
- Requires minimal additional cost.

This makes it an economical and practical alternative or complement to more sophisticated pressure detection technologies.

4.5.2 Application in Well Planning and Field Development

The insights derived from d-exponent analysis can be applied beyond a single well, contributing to field-wide pressure modelling and risk mapping:

- *Well trajectory optimisation: High*-risk pressure zones can be avoided or better prepared for in directional drilling plans.
- *Casing design:* Anticipated pressure intervals guide casing depth decisions, reducing the likelihood of casing failures.

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- *Mud program optimisation:* Anticipated pressure trends allow for better mud weight programs, improving borehole stability.

For example, if overpressure is anticipated in shale at 1,700 m, engineers can proactively increase casing points or reinforce mud weight margins, reducing risks associated with underbalanced conditions.

4.6 Rate of Change Analysis of D-Exponent Values

To enhance the sensitivity of abnormal pressure detection, the rate of change of the D-exponent and the corrected D-exponent with depth was analysed. This derivative approach helps identify transition zones, subtle pressure anomalies, and zones of sudden lithological change, which often precede overpressure.

4.6.1 Interpretation and Implications

Depth (m)	ΔD/ΔDepth (D/m)	Δdc/ΔDepth (dc/m)	Lithology	Pore Pressure (kPa)	Interpretation
1280.2	0.00049	0.00049	Shale	29,268	Normal compaction
1341.1	0.00066	0.00082	Shale	30,316	Slight deviation
1402.1	0.00098	0.00082	Shale	31,340	Transition start
1463.0	0.00148	0.00115	Shale/Siltstone	33,416	**Lithology change → Pressure rise**
1524.0	0.00082	0.00082	Shale/Siltstone	35,484	Stabilised
1585.0	0.00131	0.00115	Sandstone	38,584	**Sandstone = Overpressure**
1645.9	0.00246	0.00197	Sandstone	42,720	Severe overpressure
1706.9	0.00213	0.00164	Sandstone/Shale	47,541	Mixed lithology → Pressure spike
1767.8	0.00197	0.00131	Shale (Overpress)	53,054	**Seal breach (cap rock failure?)**

4.4 Table: Gradient Change Analysis

- *Normal Compaction Zone (up to ~1341.1 m):* Low, stable values of ΔD and Δdc (<0.0007) indicate a region of mechanical equilibrium. Drilling here reflects normal formation pressure behaviour consistent with unaltered shale compaction.

- *Onset of Transition (1341.1 m to 1463.0 m):* The ΔD/ΔDepth and Δdc/ΔDepth start to increase progressively, particularly at 1402.1 m. This correlates with rising pore pressure and signifies the beginning of a transition from normal to abnormal compaction. At 1463.0 m, the change in lithology (Shale to Siltstone) coincides with a significant increase in both ΔD and Δdc, confirming the onset of a pressure build-up due to reduced permeability.

- *Transient Stability (1524.0 m):* Slight change rate drop. This “breather” zone may represent a locally better-draining formation or a brief lithological equilibrium.

- *Overpressure Development (1585.0 m to 1706.9 m):* ΔD and Δdc values increase sharply, especially at 1645.9 m, where ΔD/ΔDepth reaches 0.00246 D/m, the steepest in the data set. This interval is dominated by sandstone, known for its lower ability to support overburden stress under rapid burial, resulting in pressure entrapment. Mixed lithology at 1706.9 m also amplifies the instability as clay lenses in sandstone can seal pressure zones, creating compartmentalization.

- *Potential Cap Rock Failure (1767.8 m):* High values of pore pressure (53,054 kPa) and slightly decreasing ΔD and Δdc rates may indicate that the overpressure has approached its cap. If seal strength is exceeded, fluids may migrate upward, increasing blowout risk. The zone, identified as overpressured shale, is likely the cap rock for the pressured formation below, and its failure could indicate **loss of containment**, a red flag for wellbore stability.

4.6.2 Drilling Optimisation Strategy Based on ΔD and Δdc Trends

- *Real-Time Monitoring:* Drilling crews can use ΔD and Δdc trends as early-warning signals. Sudden increases above 0.0015 should trigger further pore pressure estimation, increased mud weight, or reduced ROP.

- *Formation-Specific Action:* In sandstone zones, anticipate steeper Δdc rises. In transitional shale/siltstone zones, focus on balancing WOB and mud weights to delay onset of overpressure.

- *Cuttings Analysis:* When integrated with cuttings inspection and gas shows, these trends offer a robust qualitative indicator of pressure zones. A mismatch in Δdc rise and cuttings integrity (e.g., splintery shale) indicates active overpressure.

4.6.3 Comparison with Literature

Bowers (1995) emphasised that derivative methods, such as Δd-exponent, help identify compaction trends even where absolute values appear normal. Our analysis supports this. Zhang (2011) noted that where Δdc/ΔDepth exceeds 0.0015 in sandstone-rich sections, it nearly always signals the onset of overpressure. This threshold is crossed at 1645.9 m and continues to increase, validating the use of this method in pre-kick detection.

The incorporation of ΔD/ΔDepth and Δdc/ΔDepth calculations significantly enhances the resolution and sensitivity of d-exponent analysis. It allows for proactive optimisation of drilling parameters, improves safety margins, and supports decision-making under dynamic pressure conditions.

5.0 CONCLUSIONS

The research thesis focuses on optimising drilling parameters using D-Exponent analysis for the early detection of abnormal formation pressure during drilling operations. The study highlights the critical role of the D-Exponent, a surface-derived empirical tool, in identifying overpressured zones by analyzing drilling parameters such as Rate of Penetration (ROP), Weight on Bit (WOB), Rotary Speed (RPM), and mud weight. The research integrates historical well data, trend analysis, and computational modelling to develop a framework for real-time decision-making, aiming to enhance drilling safety, efficiency, and cost-effectiveness.

Key aspects of the study include:

- *Background and Importance:* The D-Exponent method is a cost-effective alternative to advanced downhole tools, particularly in resource-constrained or high-risk environments like deepwater and HPHT wells. Early detection of abnormal pressures mitigates risks such as blowouts, stuck pipe, and non-productive time (NPT).

- *Methodology:* The study employs quantitative analysis of historical drilling data, statistical modeling, and trend analysis to correlate D-Exponent values with formation pressures. Corrected D-Exponent (dc) adjusts for mud weight variations, improving accuracy.

- *Data Analysis:* The dataset spans depths from 1,219.2 m to 1,767.8 m, revealing a clear correlation between rising D-Exponent values, declining ROP, and increasing pore pressure. The corrected D-Exponent (dc) proved more reliable for detecting overpressure zones, particularly in shale formations.

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- *Industry Relevance:* The research aligns with the industry's shift toward digitalization and real-time analytics, proposing the integration of D-Exponent trends into automated drilling systems for proactive parameter adjustments.

5.1. Key Findings

Early Detection of Abnormal Pressure: The corrected D-Exponent (dc) provided early warnings of overpressure zones, with anomalies detected at 1,585 m, preceding significant pressure increases by 200+ meters. This lead time allows for proactive mud weight adjustments and well control measures.

Correlation Between Drilling Parameters and D-Exponent: A strong inverse relationship was observed between ROP and D-Exponent values. As formation pressure increased, ROP declined sharply, while WOB and RPM remained relatively stable. This confirms that D-Exponent trends reflect subsurface conditions rather than surface parameter changes. Mud weight adjustments alone were insufficient to counteract rising pore pressure, underscoring the need for early detection via D-Exponent analysis.

Lithology and Pressure Trends: Shale formations, especially at greater depths, were prone to overpressure due to low permeability and fluid entrapment. The D-Exponent effectively distinguished pressure-induced drillability changes from lithological effects.

Gradient Analysis: The pore pressure gradient exhibited a nonlinear increase beyond 1,585 m, peaking at 30.01 MPa/km in overpressured shale. The D-Exponent gradient (ΔD/ΔDepth) mirrored this trend, validating its diagnostic utility.

Comparative Advantage: The D-Exponent method outperformed conventional pressure detection tools (e.g., PWD, LWD) in cost, real-time applicability, and early warning capability. It is particularly valuable in environments where advanced tools are inaccessible.

Real-Time Integration Potential: The study demonstrated that D-Exponent trends could be integrated into real-time drilling platforms to trigger automated alerts and dynamic parameter adjustments, reducing NPT and improving safety.

5.2 Recommendations

- *Adopt Corrected D-Exponent (dc) for Pressure Monitoring:* Drilling teams should prioritise the corrected D-Exponent (dc) over the standard D-Exponent to account for mud weight variations and improve detection accuracy.
- *Implement Real-Time D-Exponent Analytics:* Integrate D-Exponent calculations into real-time drilling software (e.g., WITSML-enabled systems) to enable automated alerts and predictive modelling for overpressure zones.
- *Proactive Drilling Parameter Adjustments:* Use D-Exponent trends to adjust WOB, RPM, and mud weight preemptively. For example, gradually increase the mud weight upon detecting DC anomalies. Optimise bit selection and drilling hydraulics for overpressured formations.
- *Enhance Training and Protocols:* Train drilling engineers and rig crews to interpret D-exponent trends and respond swiftly to anomalies. Develop standardised protocols for pressure management based on DC thresholds.
- *Combine with Advanced Technologies*: Integrate D-Exponent analysis with machine learning algorithms to improve anomaly detection in complex lithologies. Explore hybrid models that incorporate LWD/PWD data where available.
- *Field-Specific Calibration:* To reduce false positives/negatives, Calibrate D-Exponent models for regional lithological variations (e.g., sandstone-shale sequences, carbonates).
- *Expand Applications:* Validate the method in horizontal and ERD wells, HPHT environments, and unconventional reservoirs to broaden its applicability.

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5.3 Conclusions

This study investigates the application of the d-exponent method for optimising drilling parameters to enable the early detection of abnormal formation pressure during petroleum exploration. Abnormal pressure zones pose significant risks during drilling operations, including blowouts, stuck pipes, and wellbore instability. By analysing drilling data, particularly the rate of penetration (ROP), weight on bit (WOB), rotary speed (RPM), and mud weight, the study uses d-exponent calculations to identify pressure transition zones. Data from a selected onshore well in the Niger Delta Basin was analysed, and Microsoft Excel was used for plotting and interpretation. The study establishes that deviations in the corrected d-exponent values serve as early warning indicators of pressure anomalies, allowing for more proactive and safe drilling operations.

Effectiveness of D-Exponent Analysis: The D-Exponent, especially its corrected form (dc), is a reliable, low-cost tool for early detection of abnormal formation pressures. It provides actionable insights before pressure-related hazards escalate.

Operational Safety and Efficiency: Proactive use of D-Exponent trends can prevent well control incidents, reduce NPT, and optimize drilling performance, leading to significant cost savings.

Digital Transformation: The study underscores the potential of integrating D-Exponent analysis into digital drilling platforms, aligning with industry trends toward data-driven decision-making.

Research Contribution: The research bridges gaps in real-time drilling optimization by validating D-Exponent analysis as a dynamic feedback tool rather than a static diagnostic method. It offers a practical framework for field applications.

Future Directions: Further studies should explore AI-enhanced D-Exponent models, validation in diverse well types, and integration with managed pressure drilling (MPD) systems.

The d-exponent analysis, particularly when corrected for mud weight, is a valuable tool for early detection of abnormal formation pressures. It enables drilling engineers to anticipate pressure transition zones and optimize drilling parameters accordingly. The study confirms that this method, when accurately applied, can enhance drilling safety, prevent blowouts, and improve cost-efficiency. Although it has some limitations, especially in complex lithologies, its integration with other formation evaluation techniques can make it an essential part of pressure prediction and well planning processes.

6.0 DECLARATION

6.1 Availability of Data and Materials

The datasets analysed during the current study are not publicly available due to confidentiality agreements with the data providers. However, anonymised versions of the data may be made available by the corresponding author upon reasonable request and with permission from the respective stakeholders.

6.2 Competing Interests

The authors declare that they have no competing interests.

6.3 Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

6.4 Authors' Contributions

David Ackah conceptualised the study, supervised the data analysis, performed the statistical and computational modelling, and contributed to the final manuscript writing.

Kwasi Opoku Boadu conducted the data collection, and prepared the initial manuscript draft.

Both authors read and approved the final manuscript.

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