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DIUNAY ZULIANI MANTEGAZINI

Pre-operational drilling test applied to carbonate reservoirs: a multi-objective optimization approach analysis of ROP and MSE

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Diunay Zuliani Mantegazini

Pre-operational drilling test applied to carbonate reservoirs: a multi-objective optimization approach analysis of ROP and MSE

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Supervisor: Prof. Dr. Andreas Nascimento.
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DIUNAY ZULIANI MANTEGAZINI

ESTA TESE FOI JULGADA ADEQUADA PARA A OBTENÇÃO DO TÍTULO DE "DOUTOR EM ENGENHARIA MECÂNICA"

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I dedicate this work to my family.

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ABSTRACT

With the discovery of Pre-salt hydrocarbon reservoirs, appeared new challenges. One of the main challenges is the necessity of optimizing drilling processes due to high related operational costs. Drilling costs are considerably high, which leads the Oil and Gas (O&G) industry to search for innovative and entrepreneur methods. The Mechanic Specific Energy (MSE) is a parameter that is being used along drilling operations; coupling of MSE and Rate of Penetration (ROP) is a method that allows identifying ideal conditions during the drilling process aimed at efficiency enhancement. In addition, the performance of the drilling process can be estimated through pre-operational tests, which consist in continuously testing applied drilling mechanic parameters, such as Drill-String Rotary Speed (RPM) and Weigh-On-Bit (WOB), looking for optimum sets would ultimately provide the most desirable ROP. Thus, the goal of this dissertation was to analyze field data from Pre-salt layers operations, using a multi-objective optimization based on a play-back methodology for pre-operational drilling tests, through the ideal combination, simultaneously aiming at the highest possible ROP and the lowest achievable MSE. In addition, the Response Surface Method (RSM) was used to explore the effects of input variables on response variables at a 95% confidence level. The results showed that the new concept of pre-operational tests based on MSE and ROP proved to be effective in the drilling process optimization. The combination between the highest ROP and the lowest MSE allows for performing an efficient drilling process. In terms of parameters setting interval in pre-operational drilling-tests, for WOB, intervals of 5 and 7 [klb] showed to be sufficient for presenting reliable results. Through the parameters obtained from pre-operational tests, it could be estimated eventual cost-saving and time-saving values ranged from USD 1,056,180.72 to 1,151,898.30 and 19.50 to 21.27 [h], respectively.

KEYWORDS: Desirability; Drill-rate test; Mechanical Specific Energy; Pre-salt layers; Oil & Gas.

RESUMO

Com a descoberta dos reservatórios de hidrocarbonetos do Pré-sal, surgiram novos desafios. Um dos principais desafios é a necessidade de otimizar o processo de perfuração devido aos altos custos operacionais. Os custos de perfuração são consideravelmente altos, o que leva a indústria de Petróleo e Gás (O&G) a buscar métodos inovadores e empreendedores. A Energia Mecânica Específica (MSE) é um parâmetro que está sendo utilizado ao longo das operações de perfuração; o acoplamento da MSE e da Taxa de Penetração (ROP) é um método que permite identificar condições ideais durante o processo de perfuração visando o aumento da eficiência operacional. Além disso, o desempenho do processo de perfuração pode ser estimado por meio de testes pré-operacionais, que consistem em testar continuamente parâmetros mecânicos de perfuração, como a velocidade de rotação da coluna de perfuração (RPM) e o peso aplicado sobre a broca (WOB), procurando obter conjuntos ótimos que fornecam a ROP desejável. Dessa forma, o objetivo desta dissertação de doutorado foi analisar os dados de campo das operações de perfuração no Pré-sal, utilizando a otimização multi-objetivo baseada na metodologia play-back para testes pré-operacionais, através da combinação ideal, visando simultaneamente o maior ROP possível e o menor MSE alcançável. Além disso, o Método de Superfície de Resposta (RSM) foi usado para explorar os efeitos das variáveis de entrada sobre as variáveis de resposta a um nível de confiança de 95%. Os resultados mostraram que o novo conceito de testes pré-operacionais baseados na MSE e ROP se mostrou eficaz na otimização do processo de perfuração. A combinação entre a mais elevada ROP e a menor MSE permite realizar um processo de perfuração eficiente. Em termos de intervalo de parametrização em testes de perfuração pré-operacionais, para WOB, os intervalos de 5 e 7 [klb] mostraram-se suficientes para apresentar resultados confiáveis. Através dos parâmetros obtidos nos testes pré-operacionais, pode-se estimar eventuais valores de economia de custo e tempo variando de 1.056.180,72 a 1.151.898,30 [USD] e de 19,50 a 21,27 [h], respectivamente.

PALAVRAS-CHAVE: Desejabilidade; Teste da taxa de perfuração; Energia Mecânica Específica; Pré-sal; Óleo & Gás.

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LIST OF ABBREVIATIONS AND INITIALS

ABM	Air-Based Muds
ANN	Artificial Neural Networks
ANP	Brazilian National Agency of Petroleum, Natural Gas and Biofuels (*Agênica Nacional do Petróleo, Gás Natural e Biocombustíveis*)
BOP	Blowout Preventer
BTU	British Thermal Units
BYM	Bourgoyone and Young model
CAPES	Coordination for the Improvement of Higher Education Personnel (*Coordenação de Aperfeiçoamento de Pessoal de Nível Superior*)
CCS	Confined Compressive Strength
DOT	Drill-Off Test
DRT	Drill-Rate Test
EFF_M	Drilling Efficiency Factor
EIA	Energy Information Administration
EOB	End-Of-Build
EOD	End-Off-Drop
FEG	Faculty of Engineering and Sciences - Campus of Guaratinguetá (*Faculdade de Engenharia e Ciências - Campus de Guaratinguetá*)
FLOW	Flow-Rate
GRG	Generalized Reduced Gradient
HAC	Heteroscedasticity and Autocorrelation Consistent
HCCME	Heteroscedasticity Consistent Covariance Matrix Estimators
HPHT	High Pressure High Temperature
HSME	Hydro-Mechanical Specific Energy
IQR	Interquartile range
KOP	Kick-Off Point
LTB	Larger-The-Better
LWD	Logging While Drilling
MD	Measured Depth
MLR	Multiple Linear Regression
MSE	Mechanical Specific Energy
MWD	Measurement While Drilling

NPT	Non-Productive Time
NTB	Nominal-The-Best
OBM	Oil-Based Muds
O&G	Oil and Gas
PDC	Polycrystalline Diamond Compact;
PDM	Positive Displacement Motor
ROP	Rate of Penetration
RSM	Response Surface Methodology
RPM	Drill-String Rotary Speed
SBM	Synthetic-Based Mud
SEOBB	Southeastern Offshore Brazilian Basins
SSI	Stick Skip Index
STB	Smaller-The-Better
TOB	Torque-On-Bit
UCS	Unconfined Compressive Strength
WBM	Water-Based Mud
WOB	Weight-On-Bit

LIST OF SYMBOLS

a_1	Formation strength and drilling fluid properties coefficient
a_2	Normal compaction trend coefficient
a_3	Under-compaction and pore pressure coefficient
a_4	Differential pressure coefficient
a_5	Constant dependent on drilling conditions and WOB behavior
a_6	Constant dependent on drilling conditions and rotary speed behavior
a_7	Teeth-cutters wear coefficient
a_8	Hydraulic coefficient
A_b	Drill-bit cross-section area
D_b	Drill-bit diameter
g_c	Mass conversion
H_L	Lower quartile
H_U	Upper quartile
K	Constant dependent drill-bit dullness, formation and drilling conditions
L	Low limit
T	Target
U	Upper limit
X	Input variables
X_1	WOB
X_2	RPM
X_3	TOB
X_4	FLOW
Y	Response variable
Y_1	ROP
Y_2	MSE
β_0	Constant coefficient
β_j	Linear coefficient
β_{jj}	Quadratic coefficient
β_{ij}	Interaction coefficient
η	Efficiency of PDM
n	Dummy factor for energy reduction

μ_b	Bit-Specific Coefficient of Sliding Friction
μ_s	Coefficient of friction of drill-string
γ_b	Inclination of the bottom hole
ΔP_b	Pressure drop across the drill-bit
ΔP_m	Differential pressure across the drill-bit

TABLE OF CONTENT

1 INTRODUCTION

The registered increasing demand for energy in general and hydrocarbons within the next few years, forecasted by different energy outlook reports in recent years, also supported the Oil and Gas (O&G) industry in exploring reserves in more challenging environments (NASCIMENTO, 2016; BP, 2023; EIA, 2023). Drilling wells in challenging environments involves high costs, mostly related to well construction and drilling processes (BARBOSA et al., 2019). Thus, it is still very important to focus on efficiency enhancements, which may allow potential time saving and operational costs reduction (SOARES; DAIGLE; GRAY, 2016).

The exploration of Pre-salt layers serves as an example of the challenges and difficulties faced during drilling activities. In this case, the challenges are related to the operations in ultradeep water, reservoirs located below 5,000 [m] and thick evaporite layers, high pressure and high temperature, offshore located (up to 300 [km] of the coast), and considerably abrasive carbonate rock reservoir (NASCIMENTO et al., 2015). In addition to the challenges indicated above, the definition of optimum drilling parameters while drilling, such as Drill-String Rotary Speed (RPM), Weight-On-Bit (WOB), Torque-On-Bit (TOB), and Flow-Rate (FLOW), it is still important and a not so a trivial activity. Within the O&G industry, these are common nomenclatures and respective abbreviations used when referring to such parameters.

The main drilling performance indicators are the rate of penetration (ROP) and Mechanical Specific Energy (MSE). ROP is an indication of how fast the well is drilled in terms of the length of hole drilled per unit of time (SOARES; DAIGLE; GRAY, 2016). While the MSE measures the amount of energy necessary to remove a unit volume of rock (TEALE, 1965). The combination between the highest ROP and the lowest MSE has not only the potential to reduce the costs of the drilling process, but also to reduce operating time. Once the drilling time is reduced, the time in which geological formations are exposed is also reduced, reducing the chances of destabilization and operational risks (GANDELMAN, 2012).

ROP prediction has been the subject of several types of research over the years. The first studies began in the 1960s. Maurer (1962) developed an ROP model for cone drill-bits, using parameters such as WOB, RPM, drill-bit diameter, and Uniaxial Compressive Strength of rock (UCS). Bingham (1965) used the drill-bit diameter, WOB, and RPM in his model, while Eckel (1967) incorporated the drilling mud effects. Bourgoyne and Young (1974) created one of the most complex ROP models using several parameters, such as the WOB, RPM, drill-bit diameter, drill-bit tooth wear, formation strength, depth, compaction, pore pressure, differential pressure, and the effect of drill-bit hydraulic jet impact force. Drilling models have been improved with technological advances, Arabjamaloei and Shadizadeh (2011) used Artificial Neural Networks (ANN) to predict ROP through field data obtained in an Iranian oil field. While Hegde and Gray (2017) used machine learning to predict and increase ROP, through input parameters such as RPM, WOB, and FLOW.

The first relation for calculating MSE was proposed by Teale (1965) for a rotary system based on experimental results. The main disadvantage of the equation presented by Teale is that it requires TOB measurement. Considering the problem presented, Pessier and Fear (1992) introduced the Bit-Specific Coefficient of Sliding Friction (μ_b) to express TOB as a function of WOB. Later, the equation originally introduced by Teale was adjusted by Dupriest and Koederitz (2005) to include the Drilling Efficiency Factor (EFF_M). In the last decade, Chen et al. (2014) developed a relation between the WOB measured at the surface and the WOB measured at the bottom of the well. While Chen et al. (2016) developed a new model for rotary drilling using a Positive Displacement Motor (PDM).

The drilling process performance can be estimated using pre-operational tests. The pre-operational tests, such as the Drill-Rate Test (DRT) and Drill-Off Test (DOT) determine the best combinations of parameters for drilling a given formation. The test consists in continuously increasing the WOB, keeping the RPM fixed in a short depth interval to obtain the ROP values (SOUTO; NASCIMENTO, 2016). However, it is important to enhance that the drilling process optimization doesn't consist simply in obtaining the highest ROP. In fact, it is necessary to search for parameters that allow drilling a phase of the well in the shortest time. Thus, the objective of this research is to obtain a multi-objective optimization capable of optimizing the drilling process, through the combination between the highest ROP and the lowest MSE, by the ideal combination of operating conditions.

1.1 OBJECTIVES

This dissertation aims to analyze and evaluate how the parameters of the drilling process affect the ROP and MSE and consequently the time and cost of the process, based on the following specific objectives:

- Analyze a field dataset from a real Pre-salt drilling operation;

- Study and apply new techniques and research about drilling optimization from drilling mechanics parameters;
- Study a multi-objective optimization based on a play-back methodology for pre-operational drilling tests;
- Develop and apply a new concept of pre-operational tests based on MSE;
- Develop and apply a methodology based on the desirability method proposed by Derring and Suich;
- Cost and time analysis based on values of mechanical parameters obtained from multi-objective optimization.

1.2 DISSERTATION STRUCTURE

The dissertation is structured as follows:

- Introduction: presents the relevance and importance of the subject in the well drilling process;
- Literature review: presents a review of the concepts used in the dissertation;
- Methodology: presents the acquisition and treatment of the dataset, in addition to the methodology developed for multi-objective optimization;
- Development: presents data analysis through the pre-operational test, multi-objective optimization, and surface response method;
- Conclusion: presents a consolidation of results.

5 CONCLUSION

In this dissertation, response surface methodology and multi-objective optimization based on pre-operational drilling tests, linked to a new recent methodology aiming at improving the drilling process through a possible ideal combination of ROP and MSE were performed. DRT methodology was mainly based on a recreation (play-back methodology) of the usual DRT from a field dataset, from a real Pre-salt drilling operation. The main conclusions drawn from this dissertation are:

- The representation of drilling parameters through 2D plots as a function of depth allowed identifying the inefficient drilling zone and the possible parameters responsible for this inefficiency;
- From the statistical analysis, it was possible to identify the input parameters that had a significant effect on the response variables. In addition, statistical models can predict all trends presented by the dataset, considering a 95% confidence level;
- The new concept of pre-operational tests based on MSE showed to promise effective improvements in the drilling processes;
- The combination of the highest ROP and the lowest MSE allows to perform an efficient drilling operation, transpering machinery, and equipment overload, and subsequently possible ways to improve operational efficiency;
- Desirability Method, as per Derringer and Suich (1980), allowed optimizing the drilling process satisfactorily, which may be extended to other operations and scenarios;
- For all WOB intervals of 3, 5, and 7 [klb] good fit of parameters was obtained, and as an interesting outcome for the industry, DRT with 5 and 7 [klb] may be sufficient to be applied in a real-time field operation;
- Through the parameters obtained from pre-operational tests, specifically for the data analyzed, it was possible to obtain eventual cost-saving and time-saving values ranging from USD 1,056,180.72 to 1,151,898.30 and 19.50 to 21.27 [h], respectively.

For future work:

- Expand this analysis to more field datasets from real Pre-salt and geothermal energy operations;
- Apply the methodology of this dissertation in a didactic drilling rig bench to test the efficiency of the proposal on a laboratory scale in real-time;
- To develop a software through the methodology presented in this dissertation to be used directly in the industry.

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