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*“Mathematical Modeling for Drilling Optimization in
Pre-salt Sections: a Focus on South Atlantic Ocean Operations”*

ANDREAS NASCIMENTO

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**MATHEMATICAL MODELING FOR DRILLING OPTIMIZATION IN
PRE-SALT SECTIONS: A FOCUS ON SOUTH ATLANTIC OCEAN OPERATIONS**

Guaratinguetá-SP

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PRE-SALT SECTIONS: A FOCUS ON SOUTH ATLANTIC OCEAN OPERATIONS**

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ANDREAS NASCIMENTO

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DEDICATORY

I dedicate this work to my family and to all that have instilled in me trust, confidence and a drive to succeed.

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EPIGRAPH

“The knowledge we learn from the masters and books. The wisdom one learns with life and with the humble...”

Cora Coralina.

“...and strong we have to be in this arduous necessity of proving knowledge...”

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ABSTRACT

Pre-salt basins and their exploration have become more and more frequently mentioned over the years, not just for their potential reserves, but also for the implicit challenges in terms of operations to face in order to make these fields commercially viable. Several research efforts aimed at addressing these related barriers, in which drilling optimization and efficiency are presented as a considerably complex area. The problematic is concentrated in the low drillability and in the high cost involved when drilling the pre-salt carbonates.

The outcome of this research is based in studies performed on top of eight pre-salt wells, addressing drilling operational time savings referenced by benchmarks and drilling mechanics parameters choosiness. The studies were based on simulations performed with penetration rate (ROP) modeling combined with specific energy (SE). The Bourgoyne Jr. and Young Jr. (1974) ROP model was used given the high errors presented for the other models, higher than 40% and, in terms of SE, the formulations from Teale (1965) and Pessier et al. (1992) were used. All these classic literature are still present in the industry and the software Oracle Crystal Ball was used as a supportive tool for the simulations.

This research yielded four important results: 1) the polycrystalline diamond compact (PDC) is the most suitable drill-bit choice for pre-salt, presenting the lowest teeth-cutters wear rate, 0.28 [%/ m]; 2) the possible spare in operational time encountered for the pre-salt operations represent a saving of approximately 13,747,550.00 [USD] for the analyzed pre-salt wells; 3) the final mathematical model developed, after the adjustments for pre-salt, foresee an improvement dropping the relative error from 36.52% to 23.12% in terms of comparing the calculated and modeled ROP with the field measured ROP; 4) the final model yielded from the combination of the ROP and SE formulations is the most adequate to be used in the industry, since it was possible to foresee an improvement by dropping the relative error even more, from 23.12% to 21.2%.

KEYWORDS: Drilling. Optimization. ROP. Efficiency. Energy. Pre-salt.

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RESUMO

As bacias do pré-sal e sua exploração se tornaram cada vez mais mencionadas ao longo dos anos, não apenas por seu potencial de reservatório, mas também devido aos grandes desafios implícitos em termos de operações a serem enfrentados para tornar estes campos comercialmente viáveis. Várias pesquisas vêm sendo desenvolvidas visando contornar estas barreiras, das quais a otimização e eficiência de perfuração se apresentam como uma área consideravelmente complexa. A problemática se concentra nas baixas taxas de penetração e no alto custo envolvido ao se perfurar as seções dos carbonatos do pré-sal.

Os resultados da pesquisa apresentados nesta tese baseiam-se em análises com oito poços do pré-sal, abordando economia de tempo operacional com base em análises referenciadas em *benchmarks* e escolhas de parâmetros mecânicos de perfuração. Os estudos foram baseados em simulações realizadas com modelagem de taxa de penetração (ROP) combinadas com energia específica (SE). Utilizou-se o modelo de ROP de Bourgoyne Jr. e Young Jr. (1974) face aos altos erros apresentados pelos outros modelos, superiores a 40% e, em termos de SE, utilizou-se o equacionamento de Teale (1965) e Pessier et al. (1992). Todas estas literaturas clássicas ainda estão presentes na indústria e o *software* Oracle Crystal Ball foi utilizado como uma ferramenta de apoio para as simulações.

Os resultados deste trabalho mostraram quatro conclusões importantes: 1) a broca de perfuração do tipo *polycrystalline diamond compact* (PDC) é a mais adequada para o pré-sal, apresentando uma taxa de desgaste de dentes-cortadores de 0.28 [%/ m]; 2) a possível diminuição de tempo de operação encontrada após análises de performance de operação pode resultar em uma economia de aproximadamente 13,747,550.00 [USD] para os poços do pré-sal analisados; 3) o modelo matemático final desenvolvido, após os ajustes para o pré-sal, pode garantir uma melhoria do erro relativo de 36.52% para 23.12% em termos de comparação entre o ROP calculado e o ROP medido durante a atividade no campo; 4) o modelo final como resultado da junção do equacionamento de ROP e SE é o mais adequado para a indústria, uma vez que foi possível garantir uma diminuição ainda maior do erro relativo, de 23.12% para 21.2%.

PALAVRAS-CHAVE: Perfuração. Otimização. ROP. Eficiência. Energia. Pré-sal.

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LIST OF ABBREVIATIONS AND INITIALS

ANP	Brazilian National Agency of Petroleum, Natural Gas and Biofuels (<i>Agência Nacional do Petróleo, Gás Natural e Biocombustíveis</i>);
BHA	Bottom-hole-assembly;
BHP	Bottom-hole pressure;
BMK	Benchmark;
BYM	Bourgoyne Jr. and Young Jr. model;
CAPES	Brazilian Federal Agency for the Support and Evaluation of Graduate Education (<i>Coordenação de Aperfeiçoamento de Pessoal de Nível Superior</i>);
CDC	Chair of Drilling and Completion Engineering;
Connec.	Connection;
CTIG	Technical Industrial College of Guaratinguetá (<i>Colégio Técnico Industrial de Guaratinguetá</i>);
D	Deviated;
DME	Mechanic Department (<i>Departamento de Mecânica</i>);
DD	Directional drilling;
Diamond impreg.	Diamond impregnated;
DOC	Depth-of-cut;
DR	Drilling rate;
Drill. prog.	Drilling program;
ECD	Equivalent circulating density;
EMW	Equivalent mud weight;
EOR	Enhanced oil recovery;
ESD	Equivalent static density;
FDP	Fast drill program;
FEG	Faculty of Engineering - Campus of Guaratinguetá (<i>Faculdade de Engenharia - Campus de Guaratinguetá</i>);
FLOW	Flow-rate;
FIT	Formation integrity test;
FP	Fracturing pressure;
GR	Gamma-ray;
HSE	Health-safety-environment;
HT	High temperature;

IBP	Brazilian Institute of Petroleum, Gas and Biofuels (<i>Instituto Brasileiro de Petróleo, Gás e Biocombustíveis</i>);
ILT	Invisible lost time;
IT	Information technology;
LOT	Leak-off test;
LWD	Logging-while-drilling;
MMbbd	Millions of blue barrel per day;
MSE	Mechanical specific energy;
MUL	Mining University of Leoben (<i>Montanuniversität Leoben</i>);
MWD	Measuring-while-drilling;
M/U	Making-up;
n/a	Not available;
NPT	Non-productive time;
OIM	Offshore installation manager;
OD	Outer diameter;
OP	Overburden pressure;
Op. c.	Operational counts;
PDM	Positive displacement motors;
PDC	Polycrystalline diamond compact;
POOH	Pull-out-of-the-hole;
PP	Pore pressure;
PU	Pick-up weight;
RAB	Rotary free weight;
RIH	Running-in-hole;
ROP	Rate of penetration;
rpm	Rotation per minute;
RSS	Rotary steerable systems;
S.	Sampling;
SE	Specific energy;
SHT	Shallow-hole-testing;
SO	Slack-off weight;
SPP_off	Stand pipe pressure off bottom;
SPP_on	Stand pipe pressure on bottom;
TBRT	Tool/ drill-bit below rotary table;
TCI	Tungsten-carbide-insert;

Temp.	Temperature;
TH	Tripping-in/ out-of-hole;
TOR_on	Torque on bottom;
TOR_off	Torque off bottom;
UCS	Ultimate compressive strength;
USD	United States dollar;
UNESP	São Paulo State University (<i>Universidade Estadual Paulista</i>);
UNIFEI	Federal University of Itajubá (<i>Universidade Federal de Itajubá</i>);
USS	Ultimate shear strength;
V	Vertical;
W2W	Weight-to-weight;
WOB	Weight-on-bit.

LIST OF SYMBOLS

$Time_{rotating}$	Total rotating/ drilling time [h];
$Time_{connection}$	Total time spent in connections [h];
$Time_{tripping}$	Total time spent in drill-string tripping [h];
$Cost_{foot}$	Final cost per drilled meter [USD/ m];
$Cost_{bit}$	Drill-bit cost [USD];
$Cost_{rig}$	Drill-rig operational cost per hours [USD/ h];
MD_{final}	Final depth taken into account [m];
$MD_{initial}$	Initial depth taken into account [m];
TVD	True vertical depth [ft];
ROP_{calc}	Rate of penetration [ft/ h];
RPM_{sf}	Rotary speed [rev/ min] [rpm];
WOB_{sf}	Translational axial force acting in the drill bit [lbf];
OD_{bit}	Outer drill-bit diameter [in];
K	Constant dependent drill-bit dullness, formation and drilling conditions [1];
WOB_{sf_t}	Translational axial force threshold necessary to initiate rock fracture [lbf];
a_1	Formation strength and drilling fluid properties coefficient [1];
a_2	Normal compaction trend coefficient [1];
a_3	Under-compaction and pore pressure coefficient [1];
a_4	Differential pressure coefficient [1];
a_5	Constant dependent on drilling conditions and WOB behavior [1];
a_6	Constant dependent on drilling conditions and rotary speed behavior [1];
a_7	Teeth-cutters wear coefficient [1];
a_8	Hydraulic coefficient [1];
h	Fractional tooth height that has been worn away [1];
S	Rock drillability or crushing strength [psi];
u_{ap}	Apparent drilling fluid viscosity [cP];
OD_{nozzle}	Drill-bit nozzle diameter [in];
EPP	Formation pore pressure [ppg];
ECD	Equivalent circulating density [ppg];
EMW	Equivalent mud weight [ppg];
ROP_{calc}	Calculated ROP using ROP models [ft/ h];
ROP_{field}	ROP retrieved from field data - observed one [ft/ h];

x_{1-8}	Related temporary parameters;
$R_{squared}$	Regression index correlation [1];
r	Residual error [1];
F_j	Jet impact force used to characterize level of bit hydraulics [lbf];
$F_{jadjusted}$	Jet impact force adjusted by the reduction factor [lbf];
γ_f	Fluid specific gravity [1];
K_a, K_b, K_c	Drill-bit constants present in the Warren (1987) model [1];
V	Average velocity of jet nozzle [ft/ s];
A_v	Ratio of nozzle jet velocity to return back-flow velocity [1];
k	Junk slot area in percentage of total drill-bit diameter [1];
$V_{back-flow}$	Total return back-flow velocity [ft/ s];
Q_{total}	Nozzle flow-rate [gal/ min] [gpm];
Q_i	Total nozzles flow-rate [ft ³ / s];
Q_f	Total return back-flow flow-rate [ft ³ / s];
$n_{nozzles}$	Number of active bit nozzles [1];
A_{nozzle}	Nozzle cross-section area [in ²];
τ_{total}	Total work performed by the forces acting in the drill bit [in-lbf];
$\tau_{rotational}$	Work performed by rotational force acting in the drill bit [in-lbf];
$\tau_{translational}$	Work performed by translational axial force acting in the drill bit [in-lbf];
F_t	Translational axial force acting in the drill-bit [lbf];
F_r	Rotational force acting in the drill-bit [lbf];
$T_{torque_{sf}}$	Drill-bit torque [in-lbf];
dt	Infinitesimal time range [min];
$d\theta$	Infinitesimal rotary angle [°];
dv	Infinitesimal drill-bit velocity equivalent to the ROP [in/ min];
ds	Infinitesimal drill-bit displacement [in];
N	Total revolution taken into account [1];
$SE_{axial-rotary}$	Drill-bit SE in terms of energy per volume of rock [lbf/ in ²];
A_b	Drill-bit cross section area [in ²];
dV_{dt}	Infinitesimal volume of rock drilled per minute [in ³ / min];
$\frac{N}{d_t}$	Total revolution per time equivalent to the rotary speed [rev/ min];
$SE_{axial-rotary_{field}}$	Drill-bit MSE in terms of energy per volume of rock [lbf/ in ²];
μ	Drill-bit sliding friction factor [1];

$MSE_{adjusted}$	Adjusted MSE to represent down-hole energy [lbf/ in ²];
MSE	Raw MSE in terms of surface energy per volume of rock [lbf/ in ²];
EFF_M	MSE efficiency in terms of percentage transmitted to the drill-bit [1].

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1 INTRODUCTION

Pre-salt basins and their exploration have become more and more frequently mentioned over the years, not just for their potential reserves, but also for the implicit challenges in terms of general operations (downstream and upstream) addressed to make these fields commercially viable. Several research efforts aimed at addressing these related barriers, but the known challenges of drilling optimization and efficiency resulted from considerably low drillability throughout the pre-salt carbonates is still present. The pre-salt market trend has been frequently explored over the years in Brazil and in Angola and, considering these countries' potential in terms of oil and natural gas, these reserves have a considerable importance in each country's economy and energy outlook. Moreover, since one of the barriers still faced is the high operational cost and the downside of drilling related events, by boosting directly or indirectly the drilling activities, the possibility of having these fields coming through economically is enhanced. Thus, studies are still under performance in several related research areas in order to model a way to allow reliable forecast and drilling parameters choosiness for efficiency assurance while performing drilling operations.

In this sense, this thesis is based in the analysis of the pre-salt carbonates operations focusing in operations that was carried in the South Atlantic Ocean. Considering the low oil prices and the also Petrobras scandal in Brazil, it is fair to say that any improvements that may result in cost savings can help even more in making these pre-salt fields to come through.

Thus, the originality of this research can be seen firstly by the pre-salt wells statistical study presented, from which an identity was drawn to refer numerically to these layers, allowing analysis to be developed. Subsequently, the research novelty was presented by a new methodology of ROP and SE models combination aiming drilling optimization. From the determination of operational time savings, of the best drill-bit to be used in these regions, of drill-bit teeth-cutters wear rate, up to in-situ geothermal and pressure profiles, a ROP model was modified accordingly, in order to reflect specifically the pre-salt wells. After the ROP model adjustments, it was combined with the SE formulations, yielding as a final result a path for determining the best set of drilling mechanics parameters, aiming to support the industry for an efficient and optimized operation, and so, potentializing costs reduction.

5 CONCLUSION

Pre-salt basins and its exploration have become more and more frequently mentioned over the years. Considered a very important petroleum-related source given the world energetic demand forecast scenario, seeking ways to support in making these fields effectively commercially viable has its value.

Supporting filling this gap, the exploration of the pre-salt reserves from related areas of the South Atlantic Ocean (in special the Brazilian and Angolan coast) has a very important role in this context, since they can be considered twin pre-salt analog clusters. Seen as a considerably high operational cost to develop these fields, due to several facts disserted, this wells can cost up to 134,000,000.00 [USD]. Hence, to address performance and possible ways for improving the efficiency of the pre-salt operation has been a route aiming support the refereed problematics.

With the support of eight pre-salt wells and thirty eight run information, statistical analyses were drawn from the gathered and filtered data, allowing the following conclusion in terms of operational performance:

- From the total of thirty eight runs, almost half of them were drilled using a PDC drill-bit. From the other types, the hybrid showed to be appropriated as well, while the TCI and diamond impregnated did not show to have good performance. The most frequent encountered problem in the drill-bits relates to broken and worn teeth-cutters.
- For some runs, the allowed drilling mechanics parameters choosiness window were going beyond the down-hole tools limitations, what certainly influenced related BHA related failure, consequently leading to operational down-time.
- The operational performance showed to still allow improvements considering the non-productive time and invisible-lost time analyzed. The following total minimum potential operational time savings was found: 37.1 [h] for well # A, 19.79 [h] for well # B, 48.8 [h] for well # C, 8.15 [h] for well #D, 22.34 [h] for well # F and 105.94 [h] for well # H, totalizing approximately 242 [h] (or 10 [days]), equivalent to 13,747,550.00 [USD].

Considering the drillability improvements, much has been understood from the used models, allowing driving the following conclusions:

- The Bourgoyne Jr. and Young Jr. ROP model is suitable for pre-salt formations, but some parameters adjustments were necessary to make it realistic for these carbonate formations. With a starting point of model fitting with 36.52% as a relative error, this model showed to correlate most. The relative error dropped to 23.12% after the pre-salt adjustments.
- The SE modeling shows to be more reliable than the ROP modeling in terms of simulation fitting. By comparing the field with the modeled data, the SE showed to have a relative error lower the one calculated for the ROP, of 21.12%.
- The reverse engineering methodology seems to be a very good way of re-building the drill-rate test curve for better visualization and drilling parameters boundaries determination.
- Considering the pre-salt well # B used for the simulation as a case study, it was possible to verify that for sake of better analysis and clarification, filtering and data split may also apply in research with similar purposes.

This thesis details a lot of step-by-step from data analysis up to final drilling mechanics parameters choosiness, allowing understanding where the room for a better performance in the pre-salt operations are.

For future work it may be interesting to address self- ROP/ SE models based on the pre-salt drilling mechanics information presented, in special on the drilling fluid details and flowing patterns, considering that the whole data set used for developing the thesis had reliable fluid mechanics information making a practicable research. Also, given the delicate narrow pressure window available for managing the equivalent circulating density and the equivalent static density, it may be very interesting to implement the usage of the manage pressure drilling concept for the pre-salt wells, what could have its applicability and well control assurance studied, in a first step, in extensive research, and subsequently, its implementation tested in real pre-salt related job. Another interesting thematic to be studied in a future work is the combination of big data concept together with the needs of reliable and in real-time decision making tools in drilling activities. By having a robust data collection of these pre-salt wells being stored as one, from activities developed and under development in the African and Brazilian coast, a very robust data set for statistical analysis would be present, helping in on-line decision making. Still in this research line, the improvement of the real-time drill-rate tests is something very promising as a new well monitoring and analysis methodology, allowing the

operational crew to have in its accustomed way a view of a new tool supporting drilling optimization and drilling efficiency enhancement. Considering these new ideas and their novelty in the industry, attached to these future works, it would be possible to foresee the deposit of new petroleum-related patents.

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