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Analysis for Optimal Bit Selection: A Case Study of a Field in Niger Delta

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Abstract: **This paper illustrates how bit selection has been perfected by the research work on hard streak in Niger Delta oil fields. This enabled division of formation into soft (sand), hard (shale) and very hard (hard streak) away from former knowledge of only soft and hard. Borehole instability is pronounced while drilling in very hard formation or hard streak.This formation is associated with siliceous-ferruginous sandstone with traces of siltstone rapped in augen of shale. Drilling through the tight streaks constituted a high risk to the drilling assembly with high axial vibrations (bit bounce) diameter and general rig operation, militating placement of Mud Motor on drill string for minimum speed. Also technical problems with old models include considerations only for soft (sand) and hard (shale) formation based on effective porosity between 5% and 20% by Skempton with disregard to less than 5% effective porosity of hard streak (hemaetitic matrix and cementation) which became major driver to our solution. The regrouping of international association of drilling companies (IADC) bit codes was a great enabler to division of rock formation into soft (sand), hard (shale or unconsolidated sandstone) and very hard (hard streak) thus making bit selection accurate. However, banking on experience, practical field documentations were made and data for this study were gathered through personal observation as a Directional Driller at Soku field. Others were from SPDC especially on Soku and Utorogu fields, NPDC's Oredo field, DPR and series of research reading in internet. The data were subjected to analytical methods, presented in tables, figures and charts. Based on the data analysis and findings, it can be stated as follows:-**

1. Sedimentary formation is hereby divided into soft, hard and very hard (hard streak) by this project models and suitable bits/drilling parameters delineated for each formation. Therefore, bits are selected with these models before and during drilling campaigns.

2. If drilling is on-going while any hole instability is encountered, you can as well query the formation and the needed bit and drilling parameters are instantly produced for solution.

3. Insert bits are very good for the hard streak, PDCs are not good because of filing effects.

Concluding, the field experiences at the Soku, Utorogu and Oredo are worth been translated to other areas were the menace of hard streak or challenging formation is very common.

4.Comparable economics has shown that IADC code 447 bit costs only $196 to drill a foot than $120,000 of PDC, with a appreciable NPT savings of $1.2M within the hard streaks of about 5,000ft.

1. INTRODUCTION

The objectives of this study are to examine the drilability issues in hard streak Formation, limitations of former workers' models to tackling very hard (streak) Formation, contribution of bit selection to advances in drilling and development of improved models to handle the drilability issues through proper bit selection.

''Drillability of a rock is the easiness to drill through it''. In his paper, R. Altindag explained that the rock brittleness is one of the most important rock properties that affect the drillability of rocks. It is supposed that the increase in rock brittleness causes the increase in penetration rate. The drillability of a rock depends on many factors. These factors can be separated as two parts depending on - machine, bit type, rotational speed, thrust, blow frequency, flushing and rock properties like brittleness, compressive strength, structure, hardness, etc. In his paper, the relationship between brittleness and drillability index, which was used in the prediction analysis of the penetration rate of rotary blast hole drills, were examined using regression analysis. It is also recognised that significant correlations exist between brittleness and the drillability index.

Prediction of performance of rock drills during the operation is one of the most important problems of any drilling job. The drillability of a rock is often defined by a set of parameters related to the drilling rate and the bit wear. They are separated into three major categories as geomechanical parameters (foliations, discontinuities, etc), machine parameters (rotation, thrust force, flushing, etc) and operating process (drilling methods, operation and maintenance of machine). Thence, the geomechanical parameters, which normally influence the drilling performance and the bit wear, cannot be altered. Consequently, the machine parameters and operating parameters can be affected by various ways.

As part of effort to tackle problems associated with hard streak phenomenon, efforts are made to study its nature and how to drill through without losing the holes or the drill string. The hard streak, for example in Soku field, which starts from about 6113ft till 6390ft or 6280ft to 7160ft in previous wells, are siliceous-ferrogenous sandstone, with traces of siltstone rapped in augen of shale and cemented by haematite. They have filling ability on the PDC because they are highly consolidated and cemented. Drilling through the tight streaks constitutes a high risk to the drilling assembly with high axial vibrations (bit bounce), hence it is the responsibility of the Directional Driller to optimize drilling parameters to minimize the overall impact.

Soku is Swampy Oil Field, rich in oil and gas.

2. THEORETICAL BACKGROUND

Two types of rock failures are common. One is induced by bit indentation and the other caused by the bit dragging or shearing. Here, there are two plane stress conditions which are assumed to be valid. The two cases were examined in this project; one is the normal stress regime: the other is the tectonic stress regime. Applying Mohr-Coulomb and tensile failure criteria, it is assumed that the compressive strength of the formation is α= 20MPa and the tensile strength is T = 0 MPa. The shear and tensile failure areas due to the cutter loading in different stress regions is thus obtained from the finite element model. It is obvious that the shear failure mainly concentrates on the downward of the cutter. However, the formation shear and tensile failure is due to the cuter loadings (p=40MPa) at t = 100s. It is clear that the maximum shear and tensile failure concentrated on the two wings of the cutter and there is basically no failure to occur in the cutter downward direction. It can then be added that the state of stress has a significant impact on the rock constitution. Therefore, when rock cutting is performed in a normal stress regime, the rock shear and tensile failures concentrate downwards. Otherwise, in a tectonic stress regime, the rock shear and tensile failures are located on two sides of the cutter.

Fast and economical penetration depends on the mineralogical structure of the rock, drilling machine, geomechanical characteristics, the driller used and the choice of drilling tools appropriate to the rock (Onan and Müftüo_lu, 1993)

According to Chevron's rock mechanics, efforts and proven strength in formation characterization have driven the development of the SeROP Predictor Tool to quantify and reduce the invisible lost-time component of drilling and tripping costs. This is accomplished by:

- Characterizing the formation to be drilled (unconfined strength, confined strength, abrasiveness, lithology, etc.)
- Selecting the right bit based on formation characterization
- Projecting the maximum target ROP in each formation
- Increasing the ROP performance of the bit on the theoretical maximum
- Maintaining optimal drilling parameters for the life of the bit.
- Knowing when to replace the bit when performance is sub-optimal.

The most important component of the SeROP Predictor Tool is the incorporation of CCS, which differs from existing ROP analysis and prediction methods that are based solely on unconfined compressive strength (UCS). UCS predictions are problematic and erroneous because UCS does not represent the "apparent' strength as the rock-bit interface. CCS is defined as the increased compressive strength of a rock from the pressure differential between the borehole pressure and the formation fluid pressure. CCS better represents the "apparent' rock strength in overbalanced drilling environments.

All things been equal, factors that drive or limit the drilling rate of penetration can be placed into two distinct categories; that is, energy input and efficiency factors that determine energy input are shown in the following ROP calculation:

$$ROP = \frac{13.33 * \mu * \mathrm{N}}{D_{\mathrm{B}}\left(\frac{CCS}{Eff_{\mathrm{M}} * WOB} - \frac{1}{Aa}\right)}$$

Where: μ = Bit-Specific coefficient of sliding Friction (unitless)

N = RPM

D_a = Bit size (inches)

CCS = Confined compressive strength of the rock (psi)

Eff_M = mechanical Efficiency of the bit

WOB = Weight On Bit (pounds)

A_B = Borehole area (square-inch)

As expressed above, the bit-specific coefficient of sliding friction (μ) expresses torque as a function of WOB and an integral function of the SeROP predictor tool is the calculation of μ and Eff_M derived from full-scale simulator tests using several different rock samples and bit types.

Bit selection remains primarily performance driven. However, using the rock mechanics approach to aid bit selection with formation characterization allows the user to quantitatively assess drilling efficiency and identify areas of ROP improvement.

Hector U et al discussed the unique ROP predictor using bit-specific coefficient of sliding friction and mechanical efficiency as a function of confined compressive strength impact drilling performance. Chevron Exploration and Production Technology Company (EPTC) initiated work on a project to improve drilling performance and pre-drill performance prediction based on a Mechanical Earth Model (MEM). Required components of this project were pre-drill bit selection, rate of penetration (ROP) prediction, and bit life predication.

3. FIELD APPLICATIONS

This thesis outlines the various analytical results obtained from applied method. Drilling of wells account for a major portion of development cost in a field (just as rig cost & crew is about 40% of drilling expense), the frequency of borehole instability, length reamed in case of underguaged hole and the mud weight used are being analyzed with respect to wellbore azimuth, inclination and TVD.

applicable world wide, identification of measurable variables affecting hardness, ductility and formation strength in different rock types as a guide to bit selection were made. Having a robust model for the bit selection encapsulating rock hydraulic, mechanical and economic factors is very paramount here.

Data from some offset wells were available and were used for the bit selection. Before considering the drill bit, failure evaluation and selection process, unconfirmed compressive strength was calculated from Sonic Log. Estimates of specific energy were calculated based on the unconfirmed compressive strength peak rate of penetration as determined.

From description of Soku field lithology, it was seen that the formation at the studied depth is well cemented together because of the unconfirmed compressive strength is far higher than all the other intervals of the well bore.

PDC bits were barbered and the borehole gauge reduced. Subsequent wells in Soku were placed under stringent bit selection with well documented problems and solutions. The drafted bit selection model for the field helped to drill the rest of the wells in good time, saving Non-Performance Time (NPT) on the rig.

Tricone bits with enhanced guage, not more than 36 hours bottom rotation time (to avoid lost of cones) were adequate to handle the hard streak.

Mineralogical structure of the rock & drilling parameters are key to selecting the bit with cutting action by compression fracturing, a practical field experience:

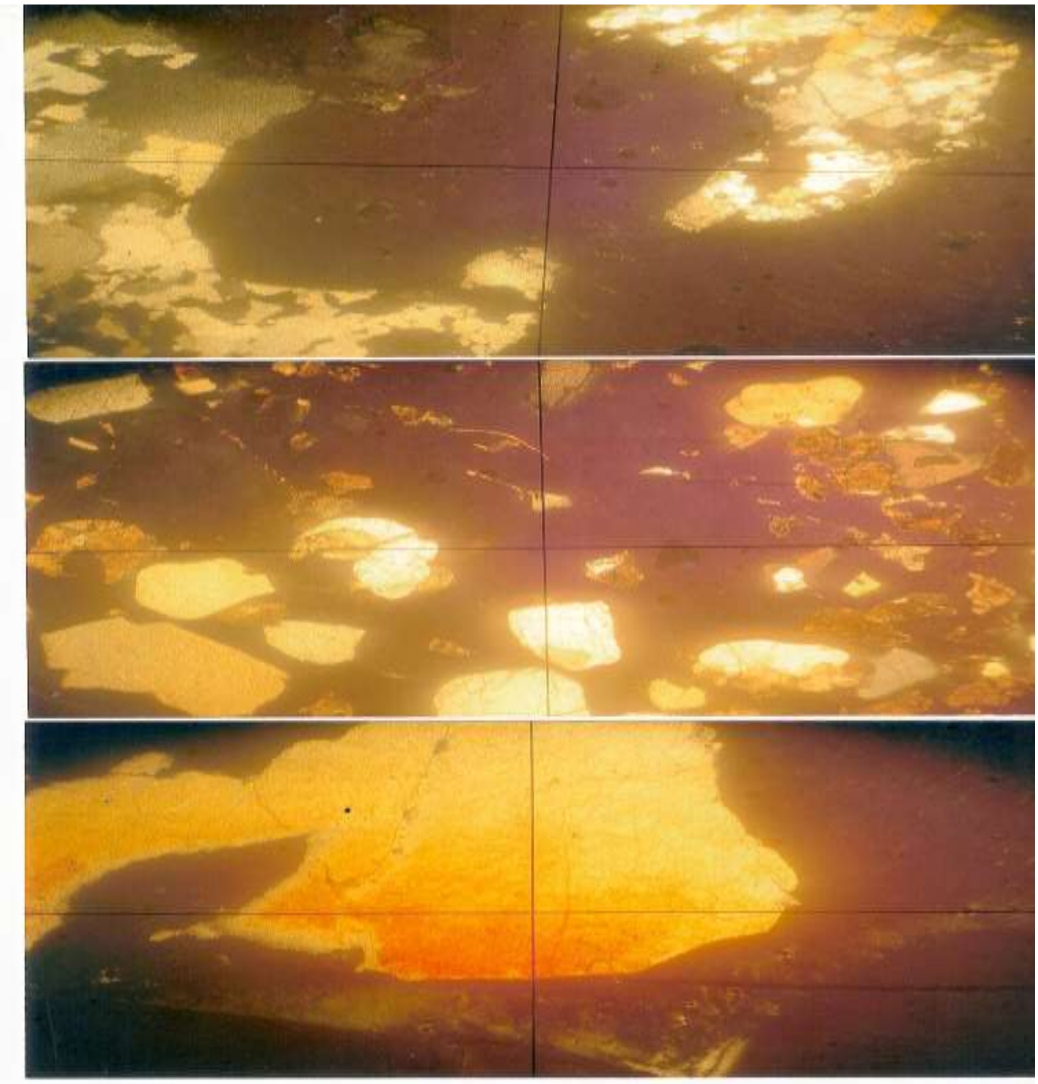


Fig 1: cross-section of rock sample in slides

Above is a cross-section slides exhibitof the hard streak constituting Quartz (monocrystalline 95%, polycrystalline 5%), stained 9% by haematite, cementation – Haematite (brown/red – oxidized and medium energy environment), traces of muscovite flake. Sediment type – quartz arenite, Rock Type – Quartzite, a constituent of a bed, Immature (not far from the source).

The rock origin, characterization, matrix (Hematite) & cementation (Hematite) enabled models on soft, hard & very hard formation.

In supportive of our experience in Soku10049, the operator aimed to drill this section in two bit runs. First run would be with a milled tooth with, tungsten carbide hard facing and enhanced diamond gauge protection (IADC 135). This bit drilled the top hole very fast and targeted at pulling the bit just before the hard streaks at +/- 6000ft. The second bit, IADC 437, 447 bit with metal to metal seal, tungsten carbide nserts, adequate gauge trimmers as well as long teeth to give some aggressiveness was to be used. This bit was expected to drill through the hard streaks up to the section TD,7250 – 10390ft (12-1/4" hole section, course length 3140ft).

Given the relatively short course length, a PDC bit with lower end blade (6-7), higher cutter size (19 – 16 mm), that would give high ROP with relatively good durability was desired and used.

Also only available was a 8-1/2" x 10-1/2" bi-centre bit from Smith. All other bit vendor's have 8-1/2" x 9-7/8" bi-centre, which does not meet the requirement of the Soku NAG wells.

The panacea, regrouping of the tricone bits was only through studies on the bit physiology as diagnosed below:

- TOOTH SERIES (Numbers 1-8): Numbers 1-3 Indicate the bit has milled steel. Numbers 4-8 indicate the bit has tungsten carbide. For insert teeth, smaller numbers indicate fewer & longer teeth for soft formation while higher numbers indicate more but shorter teeth for hard and abrasive formation.

- FORMATION TYPE (Numbers 1-4): Within each series, the formation is subdivided into four types depending on relative formation hardness. Smaller numbers indicate soft formation relative to the tooth series while higher numbers indicate hard formation relative to the tooth series.

- STANDARD FEATURES (Numbers 1-7): These numbers indicate the type of bit bearing and the presence of Gauge Protection.

From the tooth series, 1-3 (cutter type, low strength ie low uniaxial compressive strength, UCS) is in Group 1= Z_1 = 1,

4-5 (medium to hard strengthcutter i.e medium, UCS) in Group 2 = Z_2 = 2, 6-8 (hard ie high UCS) in Group 3 = Z_3 = 3. For example, a bit of 447 means UCS is 4 ie medium to hard i.e bit has Tunsten Carbide Insert Teeth. Though smaller numbers are indicative of fewer but longer teeth for soft formation (Sand/Sandstone), the next numerals 4 means formation is hard and 7 indicates bit has seal friction bearing with Gauge protection. This is an indicative of hard streak by this research.

MODIFICATION OF TEALE'S EQUATION

From:

$$ROP = \frac{13.33\mu N}{D_b\left(\frac{CCS}{Eff_m \times WOB - 1/A_b}\right)} \quad (1)$$

$$\mu = 36\frac{T}{D_b \times WOB} \quad (2)$$

$$CCS = UCS + DP + 2DP\frac{\sin FA}{1-\sin FA} \quad (3)$$

TEALE'S EQN: $Eff_m \alpha 100(Es \min / E_s)$ (4)

MODIFICATION OF TEALE'S EQN: $Eff_m = 100k(Z \times UCS / E_s)$ (5)

$$E_s = \frac{20 \times WOB \times N \times t_r}{D_b \times F} \quad (6)$$

$$Z = \begin{cases} 1, \text{ soft formation} \\ 2, \text{ hard (shale) formation} \\ 3, \text{ very hard fm (hard streak)} \end{cases} \quad (7)$$

IADC CODE

Numbers 1-8	Numbers 1-4	Numbers 1-7	C
TOOTH SERIES	FORMATION TYPE	STANDARD FEATURES	SPECIAL FEATURES

Z is the re-grouped bit Standard Tooth Series from IADC where:

Tooth Series numbers 1-3 is GROUP 1 = Z_1 = 1, for soft fm

Tooth Series Number 4-5 is GROUP 2 = Z_2 = 2, for hard (shale fm)

Tooth Series Number 6-8 is GROUP 3 = Z_3 = 3, for very hard fm (hard streak

Min. Specific Energy = Es min = ZxUCS

ROP = Rate of penetration, ft/hr

WOB = weight on bit

N = frequency, rpm

D_b = borehole diameter, in

A_b = borehole area, in^2

μ = Bit specific coefficient of sliding friction, dimensionless

T = Bit torque, ft-lbf

CCS = confined rock compressive strength

UCS = uniniaxal compressive strength of bite

DP = differential pressure

FA = rock internal angle of friction

Assumptions:

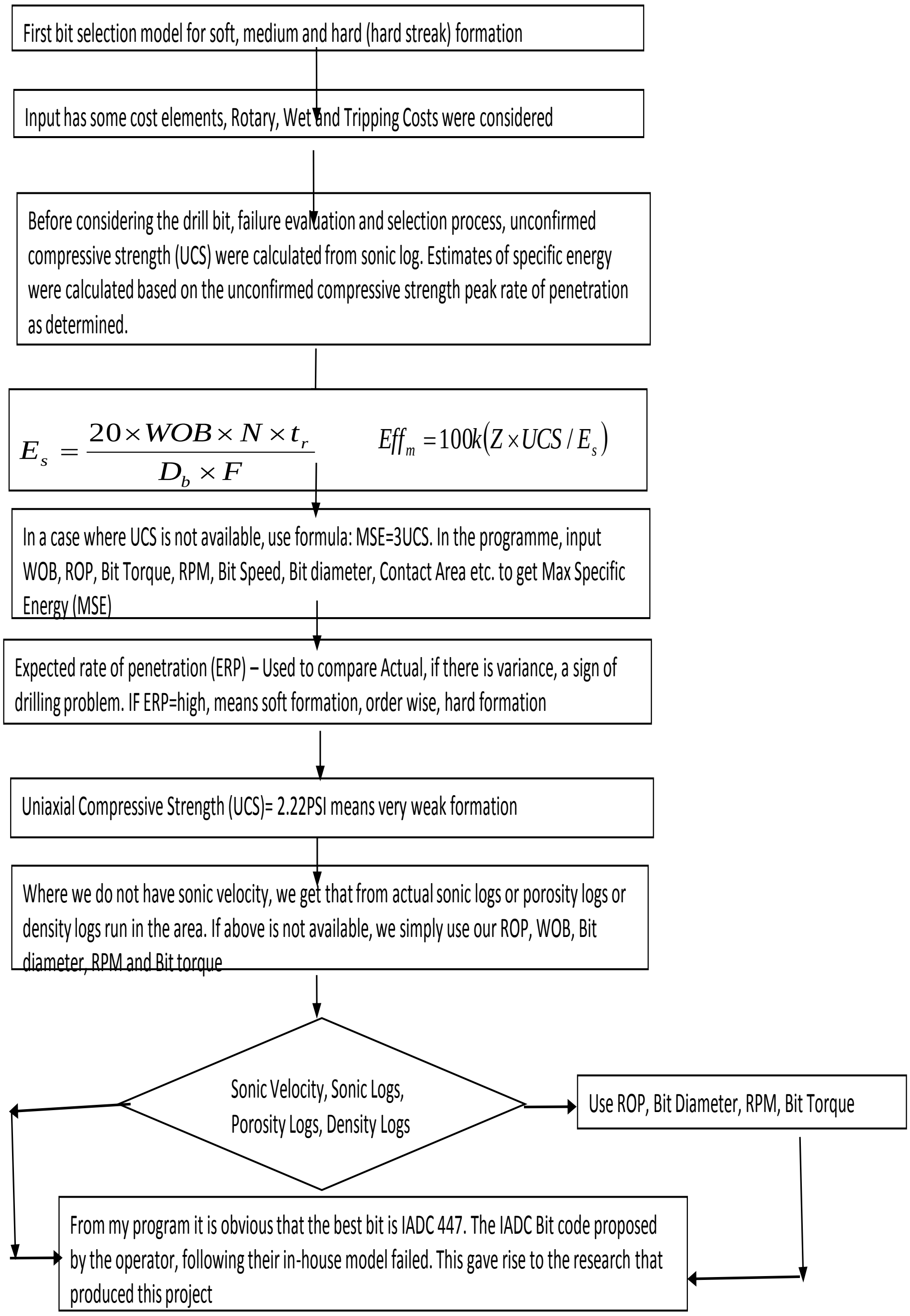
Z = Re-grouped bit standard tooth series, assumed to be 3 for hard streak.

When Z = 3, Es ~ compressive strength of bit type

k = constant that must be chosen based on when Effective Porosity<5%, k=1

tr = Rotation time (mns) ……….. obtainable while drilling

F = Footage drilled (ft) ………… obtainable while drilling



MODELS FLOW CHART

Fig.2: flow chart of our models

FIRST BIT MODEL: In this programme, three formation were involved – sand or soft formation, shale or hard formation and hard streak or very hard formation. To run the programme

1. Select any of the formation; the appropriate drilling bit in tons appears, with an initial WOB, FR, RPM, ROP etc. Each of These parameters could be changed, giving a change in other parameters. It is important to note the different types of bits that are suitable for different formation. Soft or sand formation is suitably drilled with milled tooth, shale or hard formation by PDC and Very hard formation or hard streak by insert bit (IADC Code: 437-447).

2. You may print out these values by selecting print

3. The programme is very flexible; you may change the parameters and see how they play out.

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SECOND BIT SELECTION MODEL FOR SOFT, MEDIUM AND HARD (HARD STREAK) FORMATION:

1. Input has some cost elements like rotary, wet and tripping costs were considered.
2. Before considering the drill bit, failure evaluation and selection process, unconfirmed compressive strength was calculated from Sonic Log. Estimates of specific energy were calculated based on the unconfirmed compressive strength peak rate of penetration as determined.
3. The rock strength which means Hardness of rock is determined.
4. Results:

a. Uniaxial compressive strength (UCS) = 2.22 psi means very weak formation

b. Mechanical specific energy (MSE) = 6.817 psi (means), determined bymonitoring drilling operations in site, speed limit needed to avoid vibration, optimal bit torque needed to enable rate of penetration, to give good idea of formational strength.

c. In a case where UCS is not available, we use formula: MSE=3UCS. In the programme, input WOB, ROP, Bit Torque, RPM, Bit Speed, Bit Diameter, Contact Area, etc to get MSE.

d. Expected Rate of Penetration (ERP) is used to compare actual, if there is variance, it is a sign of drilling problem. If ERP = High, means soft formation, order wise, hard formation.

Where we do not have sonic velocity, we could get that from actual sonic log run or porosity log or density log. If above is not available, we simply use our ROP, WOB, Bit Diameter, RPM, and Bit Torque.

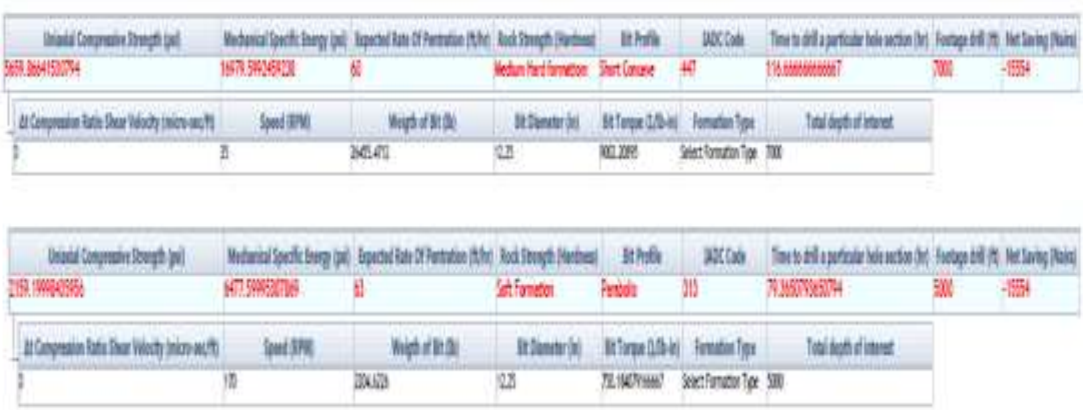

Fig 3: Results Of Second Bit Selection Model

SOURCE: AUTHOR

Note: From our programme, it is obvious that the best bit is IADC 477. The highlighted IADC 415 proposed by SHELL, following their in-house model failed us while on the rig**.**

Comparable economics run on the IADC 447 code bit costs only $196 to drill a foot than $120,000 of PDC, thereby saving $1.2M within the hard streaks of 5,000ft.

4. CONCLUSIONS

Arising from the analysis and finding, it is concluded that this project has established the facts that rock mineralogical structure (Petrology) helped us to understand the matrix/cementation and rock constituents that make up the hard streak. The rock formation is now grouped into 3 – soft, hard and very hard Formation to accommodate hard streak. The developed Models helped in proper bit selection for soft, hard and very hard Formation (hard streak). From comparable economics, the IADC code 447 bit costs only $196 to drill a foot than $120,000 of PDC, thereby saving $1.2M within the hard streaks of 5,000ft.

The by-product of this research is that about 3,000ft to NAG well Reservoirs or 7,000ft from surface on land, in gas prone areas of Niger DeLTA (Soku and Utorogu), hard streak is eminent.

We need to plan to drill the hard streak in 12 ¼'' hole section with a steerable BHA so as to reduce vibrations/shocks generated by abrasive sands/hard streaks leading to tool failures/twists in drill string.

Siliceous Formation and Hard Streak should be drilled with Tricone Bit (IADC Code 437 or 447 because of their fracturing ability on the streak. **We d**o not run PDC bits within the hard streak areas because they will be destroyed. We also advice that Tricone bits should not run above 36 hours to avoid lost of cones.

By abiding to the recommendations above, Non-Performance Time (NPT) is reduced.

Benefits of this study to Drilling Industry:

- Saved lots of time and money (round tripping) from wrong choice of bits.
- Good knowledge of the nature of hard streak is understood.
- A vibration occurrence as a result of the streak was also handled and better guide on good selection of bit is well played out and purpose of mud motore on the bit is well understood.
- The fact that PDCs are not recommended in hard streak environment was obvious. Thus the tricone bits recommended could not run above 36 hours in the well or face lost of cones.
- The recommended bit with enhanced gauge protections, preferably needed to prevent under-gauged hole. The bit, IADC (447 or 437) with metal to metal seal, tungsten carbide inserts, adequate gauge trimmers as well as long teeth needed to provide some aggressiveness.
- Above all, Non-Performance Time (NPT) is reduced.

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Nomenclature

Bbl A standard measure of crude oil
ECD Equivalent circulating density
MD Measured Depth
TVD True Vertical Depth
API American Petroleum Institute
ROP Rate of Penetration
RPM Rotation Per Minute
BHA Bottom Hole Assembly
DPR Directorate of Petroleum Resources
NNPC Nigerian National Petroleum Corporation
3D Three Dimensions
4D Four Dimensional (4th dimension being time lapse)
PSC Production Sharing Contract
STOOIP Stock Tank Oil in Place

μ = Bit-Specific coefficient of sliding Friction (unitless)
N = RPM
$\mathbf{D_a}$ = Bit size (inches)
CCS = Confined compressive strength of the rock (psi)
$\mathbf{Eff_M}$ = mechanical efficiency of the bit
WOB = weight on bit (pounds)
$\mathbf{A_B}$ = Borechole area (square-inch)
ΔP = pressure drop, psi
P_D = dimensionless pressure drop
P_i = initial reservoir pressure, psi
$\bar{P}$ = average reservoir pressure, psi
r_{eD} = dimensionless reservoir radius based on wellbore radius
k = permeability, md
k_r = relative permeability
μ = viscosity, cp
H = formation thickness, ft
A = area, ft^2
ϕ = porosity, fraction
c_t = total compressibility, psi^{-1}
t_p = production time, hr
t_{DA} = dimensionless time based on area

Subscript

o oil
w water
g gas
T total

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