Optimization of Slim-Hole Drilling Parameters in the Bach Ho Field

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ABSTRACT

Over the years, hundreds of wellbore diameters of 165.1 mm had been drilled into the basement formation of the continental shelf of Vietnam. The low drilling performance is that the drill string often operates in unstable stability due to the drilling parameters such as the weight on the bit, the rotation speed, and the mud pump flow rate, which are not suitable, leading to a decrease in drilling performance as well as low the penetration rate. Therefore, reasonable drilling parameters have been optimized so the drill string works stable when drilling into the basement formation rock. In this study, the mapping theory method is applied to investigate the dynamic stability of the drill string of these wells when drilling into the basement formation rock. The dynamic stability of the drill string is essential to determine the optimal drilling parameters when drilling into the basement formation. The results show that for drilling wellbore diameter of 165.1 mm, the optimal drilling parameters have been determined as weight on the bit (WOB) of 4.65 tons, rotary per minute (RPM) of 93, mud pump flow rate (Q) of 16.1 l/sec.

KEYWORDS: *drilling parameters; slim wellbore; White Tiger field; dynamic stability of drill string*

1 INTRODUCTION

A few decades ago, several literatures studied the optimal drilling parameters, and the level of their parameters influenced the penetration rate, which optimized the drilling parameters. These methods achieved a certain result due to many constraints such as methodologies, equipment, and technology used in the research. The previous research is directly summarized as follows statistics of actual data of bit tooth wear, selection of the bit type that is high performance for drilling wells by applying the drilling parameters. In this case, the physical and mechanical rock properties are divided according to the penetration rate level of the geological cross-section of these wells. The obtaining and processing of drilling data were analysed on a computer. During the processing of statistical drilling data, there were still significant changes, especially when using many different bit types. Drilling parameters were determined through the experimental relationship of the rock destroy efficiency and the capacity of the bit performance. This study implemented many experiments based on the model

and in the field. Based on the experimental results, the experimental penetration rates formula was proposed to determine the optimal drilling parameters. The disadvantage of this method did not consider the change in rock properties at the bottom hole and did not interpret the dependent relationship parameters to find the optimal weight on the bit and rotational speed. The direct determination of drilling parameters was mainly the weight on the bit based on experiments on the mechanical rock properties, and the contact area between the tooth bit and the surface rock at the bottom hole. The determination of the weight on the bit is to ensure an effective destroy rock formation. This method has some disadvantages as it did not consider the drilling capacity and bearing durability of the bit. In the last few decades, there have been many approaches to obtain optimum drilling parameters based on optimization equations, linear equations, and nonlinear equations. Graham and Muench (1959) investigated the weight on the bit and rotary speed combination to derive empirical mathematical descriptions for the bit life expectation and the penetration rate model as a function of depth, rotary speed, and weight on the bit. Maurer (1962) developed the rate of penetration equation for roller-cone type bits that consider the rock destroy mechanisms. The model was based on the perfect cleaning hole condition at which all the rock cutting is removed between the tooth impacts. The penetration rate model is related to the weight on the bit, rotary speed, and drilling depth in terms of considering hole cleaning circumstances. Galle and Woods (1963) evaluated the influence of best constant weight on the bit and rotary speed for the lowest drilling cost that developed mathematical correlations. The graph for field applications determined the best combinations of constant weight on the bit and rotary speed. Eckel (1968) developed the penetration rate model for the micro bit study in terms of a function of pseudo bottom hole or near-nozzle Reynolds number. The model was independent of the weight on the bit, rotary speed, and differential pressure at the bottom hole. Reed (1971) achieved a variable weight-speed optimum drilling model, which was solved using a Monte Carlo scheme for the lowest cost per foot drilling. Bourgoyne and Young (1974) constructed a linear penetration rate model and achieved a multiple regression analysis of drilling data to determine the optimum weight on the bit, rotary speed, and bit hydraulics. Simmons (1986) performed the first real-time drilling optimization studies based on the application of all possible means at the time of study to get optimum drilling parameters at the rig site. Warren (1986) developed the penetration rate model that related the effect of both initial chip hold down and cuttings-removal process. The penetration rate model is derived from two parts working with perfect hole cleaning assumption. The first term performed the maximum penetration rate by supporting the weight on the bit effect. The second term considered tooth penetration into the formation rock. The penetration rate model was applied to the experimental data for both steel tooth and insert bit types. Miska (1988) developed three governing differential equations such as penetration rate, rate of teeth wear, and rate of bearings wear. The finding concluded that these expressed equations have been completely used for determining and optimizing purposes that some conditions were satisfied such as adequate bottom hole cleaning, properly rock bit selected to drill the formation, and macroscope-homogeneous formation. Maidla and Ohara (1991) investigated a drilling model on offshore drilling data and then compared the results with Bourgoyne and Young's drilling model. The purpose of the study was to select the bit, bit bearing, weight on the bit, and rotary speed to minimize the drilling costs. Ursem et al., (2003) presented an operator and service company using state-of-the-art technology within the scope of a real-time operations centre. Rommetveit et al., (2004) developed an innovative drilling automation and monitoring system. All surface drilling data and subsurface drilling data were used to optimize the drilling process. The model was a bit load optimization module that modulated rotary speed and weight on the bit and observed the changes that influenced the

penetration rate. Dupriest and Koederitz (2005) used effectively the mechanical specific energy (MSE) concept in evaluating the drilling efficiency of bits on a real-time basis. The finding developed a system allowing the driller to continuously monitor MSE predicted through surface drilling parameters measurements with other normal mechanical drilling logs. Due to the complicated dynamic drill string while drilling into the formation, most of the previous approaches were based on major factors such as weight on the bit, rotary speed, bit tooth wear, and bit profile. It is under these conditions that the simulation or construction of the penetration rate models for the drilling process often does not fully reflect the parameters included. The above studies on drilling parameters in any direction have not reflected the dynamic stability of the drill string and the energy consumed to destroy the surface rock at the bottom hole. At the same time, the previous studies have not shown the simultaneous influence of all factors affecting the efficiency of the bit. Selecting the drilling parameters such as weight on the bit, rotary speed, and mud pump flow rate based on the dynamic stability of the drill string for destroying rock formation has mitigated the above limitations.

2 GEOLOGICAL CHARACTERISTICS OF BASEMENT RESERVOIR

Most basement rocks are hard and brittle. Fractures, faults, and vugs have created the porosity of the basement formation. In the continental shelf of Vietnam, the fractured basement formations are located under the unconformities and on the highs of the uplifted blocks, which were weathered and eroded. Younger sediments such as Oligocene formations that played an important role, such as source rocks and cap rocks (Fig.1), which covered these basement formations. Two types of rocks, such as metamorphic and igneous rocks characterized the basement rocks of Cuu Long basin. The igneous rocks consist of diorite and quartz diorite (granite), which were formed in the active continental margin arc setting. Metamorphic rocks are gneiss, and they were found in Dragon and White Tiger fields (Nguyen et al., 2008; Nguyen and Nguyen, 2008). These rocks included three complexes, which are called Hon Khoai, Dinh Quan, and Ankroet. These rocks were formed about 90 million to 240 million years ago (Hoang, 2008). The Ankroet complex shows the highest oil productivity, next is the Dinh Quan complex, and the lowest productivity is the Hon Khoai complex (Tran et al., 2008). In the White Tiger field, the oil-bearing zone varies from 3700 m to 4450 m in depth at the boundary of the reservoir and from 4000 m to 4200 m in depth at shallower intervals.

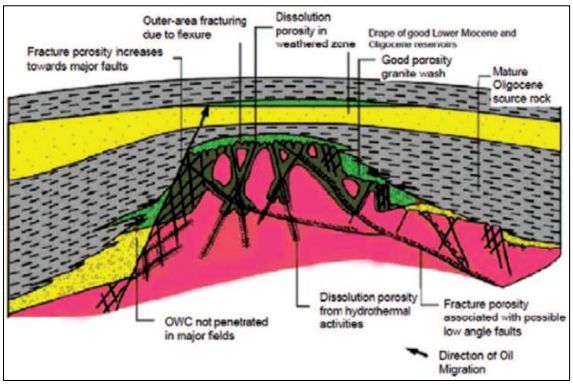

Fig.1. Petroleum plays in Cuu Long Basin with fracture porosity distribution of the Basement reservoir (Ngoc, 2014).

3 MAPPING THEORY

Most natural phenomena are nonlinear. For example, models of weather and turbulence of fluids are the most general for nonlinear processes. The value of nonlinear effects in many physical phenomena can be easily explained through the analysis of function in mapping theory (Bazykin et al., 1989; Arnold et al., 1999; Tian Ma et al., 2005). The branched function in mapping theory was expressed as follows:

$$x_{n+1} = rx_n(1 - x_n)$$

Where r is the controlled parameter.
x_n is the correlation of the nth known number with the previous number.

The dynamic properties of branching functions are complex and play an important role in the study of a general theory of nonlinear processes. In 1978, the scientist Feygenbak, with the help of a computer, discovered many interesting properties of branched functions.

The result shows that by changing the control parameter r, the function $f(x)= rx_n(1- x_n)$ had certain variations as seen in (Fig.2). When $0<r<1$, the x_k sequence value of the function f(x) after a transition period will quickly converge to a stable and stable fixed-point x=0, and it did not depend on the condition initial case x_0. When $1<r<3$, the sequence x_k converged to a fixed-point $x\neq0$ and it did not depend on the initial condition x0. When $3<r<3.45$, then after the transition period x_k will fluctuate between two fixed points x_1, $x_2\neq0$ (the function f(x) has a change in the statement). When r > 3.45, the sequence of x_k values represents the derivative function f(x), which will have an increasing number of fixed points and gradually chaotic motion (no fixed points). The above properties of the branching function represent the working state of a dynamic drill string system, which is represented by the function f(x) when r has been changed. When $0<r<1$, the dynamical drill string system always operates in a stability. When $1<r<3$, the dynamical drill string system is operated from a stability state to unstable stability when there are effects of peripheral conditions. When $3<r<3.45$, the dynamic drill string system operates in an unstable state. When $r>3.45$, the dynamical drill string system falls into a chaotic statement as it has lost controllability. In addition, it is easy to know that when $x_n>1$, the value of x_{n+1} will be negative. To avoid this nonphysical case, it is necessary to have a condition that limits the change of the variable x as $0<x<1$.

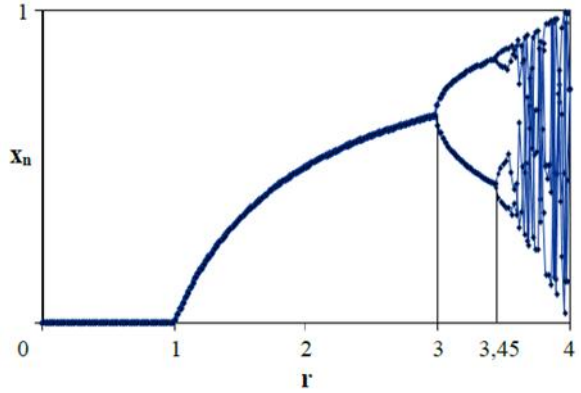

Fig.2. The repeated values x_n according to the control parameter r.

4 INVESTIGATING THE DYNAMIC STABILITY OF THE DRILL STRING

The characterization of the drill string while drilling wells is that it is easy to dynamic instability of the drill string. This leads to reduce the penetration rate and deflection of the wellbore compared to the design, as well as changes in weight on the bit due to changes in the physical and mechanical properties of the formation rock. When the weight on the bit is increased to a certain critical value, the steady state of the dynamical drill string to be drilled changes suddenly. Mapping theory methodology can be applied to evaluate the actual dynamic stability of the drill string.

5 APPLICATION OF MAPPING THEORY

To study and evaluate the dynamic stability of the drill string by mapping theory (Arnold et al., 1999), select the branched function to reflect the drill string rotates to destroy the formation rock by bit, the model is expressed as follows:

$$\mathrm{ROP_{n+1}} = \mathrm{rROP_n}(1 - \frac{\mathrm{ROP_n}}{\mathrm{ROP_{max}}})$$

Where $\mathrm{ROP_n}$ is the penetration rate of the nth, m/h, r is a controlled parameter, which depends on the interaction relationship between geological conditions, structure of bottom hole assembly, shape, and length of the wellbore and drilling technology, r is also determined by the least squares method through processing the actual drilling data. The states of the dynamical drill string system can occur corresponding to the variation of r as follows (Blank, 1990): When the r value is varied between zero and one, the dynamic stability of the drill string system is maintained, the bit drilled formation at the bottom hole is in a stable steady state. When r is varied between 1 and 3, the dynamical drill string is easily transitioned from a stability statement to a less stability statement. When the r value is varied between 3 and 3.45, the dynamic stability of the drill string system is operated in a state of dynamical instability. When the r value is more than 3.45, the dynamic drill string system is operated in a state of serious instability, the drill string and the bottom hole assembly always can get some drawbacks such as a broken roller cone bit, broken drill pipe of the drill string and damaged other components of the bottom hole assembly.

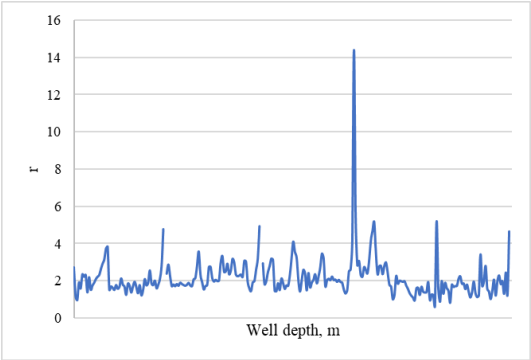

Fig.3. The controlled factor of r along wellbore diameter 165.1 mm of Well A.

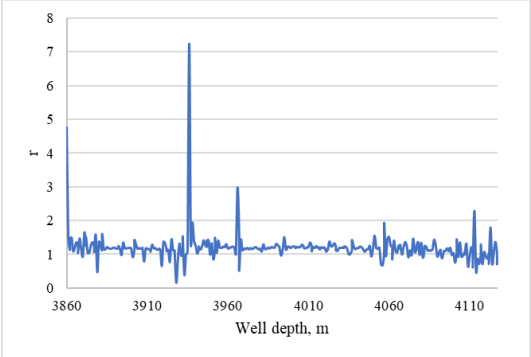

Fig.4. The controlled factor of r along wellbore diameter 165.1 mm of Well B.

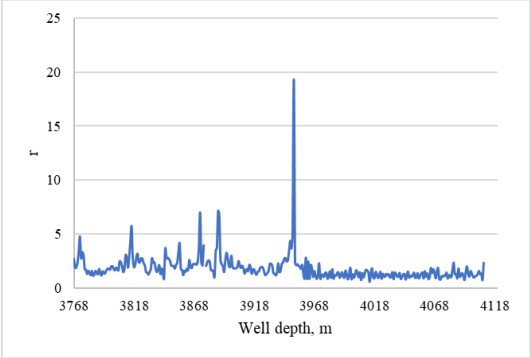

Fig.5. The controlled factor of r along wellbore diameter 165.1 mm of Well C.

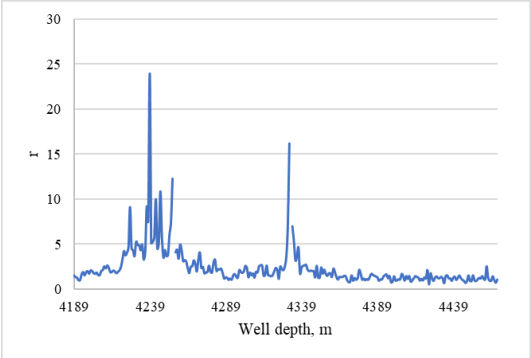

Fig. 6. The controlled factor of r along wellbore diameter 165.1 mm of Well D.

The results analysed show that when the environment changed, the drilling conditions of the bits and the values of the drilling parameters changed according to the well depth, leading to a change in the statement of the dynamic stability of the drill string. The drilling parameters applied to drill the formation, are mismatches that cause the low drilling performance of the dynamical drill string based on the investigation of the dynamic stability of the drill string. This instability of the dynamic drill string caused the low penetration rate in the drilling wellbore diameter of 165.1mm. Thus, when the dynamical drill string system is drilled in the basement formation rock in the White Tiger field, it is always unstable. The instability of the dynamic drill string is caused to uncontrol the wellbore trajectory when the well depth and the horizontal departure increase, and they have an impact on the actual drilling efficiency.

6 SELECTION OF DRILLING PARAMETERS THROUGH DRILLING MODELS BASED ON DYNAMIC STABILITY OF THE DRILL STRING

When drilling into the formation rock, the value of weight on the bit is not fully applied to destroy the basement formation, a part of the weight on the bit is lost due to the friction between the drill string column and the alongside the wellbore, and other part of the weight on bit lost due to the vibration of the drill string column, especially when drilling by a tritone bit (Sharipov, 1995). The drilling parameters including the rotation speed, and mud pump flow rate are similar to the weight of the bit to investigate the stability of the drill string condition. To determine the suitable drilling parameters in the field based on the types of bits, and the bottom hole assembly in terms of the dynamical stability of the drill string, the function branching has chosen a nonlinear model (Dao, 2006):

$$\frac{dx}{dL} = F(x) = rx\left(1 - \frac{x}{x_{max}}\right) - x_0 \quad (1)$$

Where x_{max} is the maximum value of drilling parameters.
r is the controlled parameter.
x_0 is drilling parameters lost due to friction and vibration in the wellbore.
L is the measured depth, m.
In terms of weight on the bit, the formula can be expressed as follows:

$$\frac{dWOB}{dL} = F(WOB) = rWOB\left(1 - \frac{WOB}{WOB_{max}}\right) - WOB_0 \quad (2)$$

Where;
WOB_{max} is the maximum weight on the bit, tons
r is the controlled parameter.
WOB_0 is the weight on the bit spent on friction and vibration in the wellbore.
L is the measured depth, m.

Solving the differential equation (1) in terms of the condition WOB = WOB_1, the equation obtained as

$$\begin{cases} WOB_x = \frac{1}{\beta}\frac{\beta WOB_1(r+\alpha)-(r^2-\alpha^2)-[\beta WOB_1(r-\alpha)-(r^2-\alpha^2)]e^{-\alpha x}}{[\beta WOB_1-(r-\alpha)]-[\beta WOB_1-(r+\alpha)]e^{-\alpha x}} \\ \alpha = \sqrt{r^2 - \frac{4WOB_0 r}{WOB_{max}}};\ \beta = \frac{2r}{WOB_{max}} \end{cases} \quad (3)$$

The catastrophe for the selected models changed the levels of the weight on the bit according to well depth:

$$\frac{dWOB}{dL} = \frac{d^2WOB}{dL^2}$$

There is the following system as Eq (2)

$$\begin{cases} \mathrm{rWOB}\frac{\mathrm{WOB_{max}}-\mathrm{WOB}}{\mathrm{WOB_{max}}} - \mathrm{WOB_0} = 0 \\ 1 - \frac{2\mathrm{WOB}}{\mathrm{WOB_{max}}} = 0 \end{cases} \quad (4)$$

$$\mathrm{WOB_0} = \frac{\mathrm{rWOB_{max}}}{4} \quad (5)$$

Equation (2) is derived as the following equations:

$$\frac{\mathrm{dWOB}}{\mathrm{dL}} = \frac{\mathrm{WOB_{n+1}} - \mathrm{WOB_n}}{\Delta \mathrm{L}} = \mathrm{rWOB_n}\frac{\mathrm{WOB_{max}} - \mathrm{WOB_n}}{\mathrm{WOB_{max}}} - \mathrm{WOB_0}$$

$$\mathrm{WOB_{n+1}} = \mathrm{WOB_n}(1 + \mathrm{r}\Delta \mathrm{L}) - \frac{\mathrm{r}\Delta \mathrm{L}\mathrm{WOB_n^2}}{\mathrm{WOB_{max}}} - \mathrm{WOB_0}\Delta \mathrm{L}$$

Set the values:

$$\mathrm{a_1} = (1 + \mathrm{r}\Delta \mathrm{L}); \mathrm{b_1} = \frac{\mathrm{r}\Delta \mathrm{L}}{\mathrm{WOB_{max}}}; \mathrm{Z_1} = \mathrm{WOB_0}\Delta \mathrm{L}$$

Substituting the values a_1, b_1, and Z_1 into the drilling model, which is expressed

$$\mathrm{WOB_{n+1}} = \mathrm{a_1}\mathrm{WOB_n} - \mathrm{b_1}\mathrm{WOB_n^2} - \mathrm{Z_1} \quad (6)$$

Derive the same for the rotation speed (RPM) and mud pump flow rate (Q) as follows:

$$\mathrm{RPM_{n+1}} = \mathrm{a_2}\mathrm{RPM_n} - \mathrm{b_2}\mathrm{RPM_n^2} - \mathrm{Z_2} \quad (7)$$

$$\mathrm{Q_{n+1}} = \mathrm{a_3}\mathrm{G_n} - \mathrm{b_3}\mathrm{Q_n^2} - \mathrm{Z_3} \quad (8)$$

7 DETERMINATION OF EXPERIMENTAL COEFFICIENTS FOR DRILLING MODEL

The field data including the weight on the bit, mud pump flow rate, and the rotation per minute were collected per meter from wellbore diameter of 165.1 mm for drilling production intervals. Several wellbore diameters of 165.1 mm to drilling the Oligocene formation in the field used the same conventional bottom hole assembly (BHA). Only the major drilling parameters consist of the weight on the bit, mud pump flow rate, and rotation per minute, which allow to investigate the real-time level of dynamic stability of the drill string. Based on that, the drilling parameters collected are the weight on the bit in tons, mud pump flow rate in l/sec, and rotation per minute. Based on Eqs (6, 7, 8), the drilling data in the field including weight on the bit, mud pump flow rate, and rotational per minute were collected from the surface sensor of these wells for drilling intervals in the basement formation of the White Tiger field based on wellbore diameter 165.1 mm when drilling by the rotor. The determination of these coefficients included a_1, a_2, a_3, b_1, b_2, b_3, Z_1, Z_2, Z_3 through the regression analysis. The data in the field including weight on the bit, rotational speed, and mud pump flow were obtained per meter of well depth drilled (ΔL=1m). In terms of bit 165.1 mm when drilling wells by the rotor, the models of drilling parameters were expressed as follows:

$$WOB_{n+1} = 0.287 + 0.922WOB_n + 0.00350WOB_n^2 \quad (9)$$

$$RPM_{n+1} = -0.31 + 1.03RPM_n - 0.000288RPM_n^2 \quad (10)$$

$$Q_{n+1} = -2.78 + 1.41\,Q_n - 0.0144\,Q_n^2 \quad (11)$$

The unit used in equations (9) to (11) for the WOB of tons, the RPM, and Q of liters per second, l/sec. Based on the results of coefficients for the drilling parameters of models, it is possible to calculate and determine the values of the weight on the bit, rotational speed, and optimal mud pump flow. When bit works under these operating drilling parameters, it ensures that the dynamical drill string system is always in a stable state. To ensure a dynamical drill string always works in a stable statement, it needs to have the following conditions:

$WOB_{n+1}=WOB_n$; $RPM_{n+1}=RPM_n$; $Q_{n+1}=Q_n$

Eqs (9, 10, 11) can be described through Figs (7, 9, 11) when drilling wellbore diameters by the bit 215.9 mm in the basement formation through drilling rotor method. The intersection between two lines in the figure is determined by the values of the drilling parameters. However, the lines shown on the graph intersect at two points, so it is necessary to express the next step to select an only value of the drilling parameters. Based on the selected drilling models for the weight on the bit, rotation speed, and mud pump flow, and based on the condition, if derivative F'(x, r) <0, the dynamic stability of the drill string is stable, when derivative F'(x, r)>0, the dynamic stability of the drill string is considered unstable. The differential equations can be expressed through Eqs (12, 13, 14) based on Eqs (9, 10, 11) as follows:

The well is drilled by the rotor method in terms of the bit 215.9 mm.

$$\frac{dWOB}{dL} = -0.078WOB_n + 0.00350WOB_n^2 + 0.287 \quad (12)$$

$$\frac{dRPM}{dL} = 0.03RPM_n - 0.000288RPM_n^2 - 0.31 \quad (13)$$

$$\frac{dQ}{dL} = 0.41Q_n - 0.0144Q_n^2 - 2.78 \quad (14)$$

Fig.7 is described based on the weight on the bit model as Eq (9), this figure shows that the straight line and the parabolic line of weight on the bit intersected at two points with the order of (WOB_n, WOB_{n+1}) such as (17.64 tons, 17.64 tons), and (4.65 tons, 4.65 tons), respectively. The optimal weight on the bit of the drilling parameters is 4.65 tons because the WOB of the bit 165.1 mm is below 15 tons according to company recommendation. Similarly, Fig.9 is constructed based on the rotational speed model as Eq (10), this figure illustrated that the straight line and the parabolic line of rotational speed intersected at two points with the order of (RPM_n, RPM_{n+1}) such as (12, 12), and (93, 93), respectively. The optimal rotational speed is 93 rpm because the rotational speed of the bit 165.1 mm ranges between 60 rpm and 100 rpm according to company recommendation. Fig.11 described through the mud pump flow rate model as Eq (11), this figure shows that the straight line ($Q_{n+1}=Q_n$) and the parabolic line of the mud pump flow rate model intersected two points such as (12.4 l/sec, 12.4 l/sec, and (16.1 l/sec, 16.1 l/sec). Based on the differential equations (12, 13, 14), construct the graphs in Figs (8, 10, 12). On the left are the graphs of the differential equations corresponding to the drilling parameters such as the weight on the bit, mud pump flow rate, and the rotation per minute of the drill string, on the right of the graph is the line representing the length, L, and

corresponding to the drilling parameters. To find the length, L, solve the differential equation relating the length, L, to the drilling parameters.

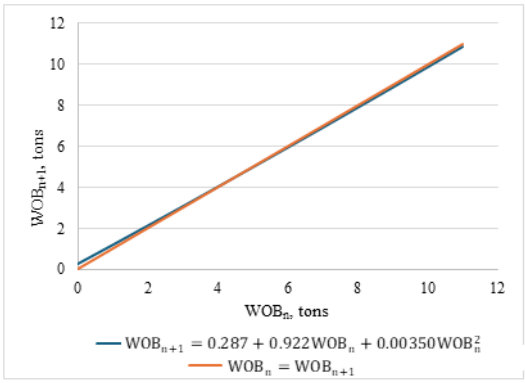

Fig.7. Relationship between WOB according to the drilling rotor of bit 165.1 mm.

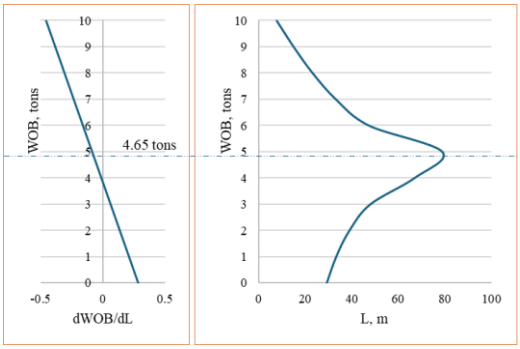

Fig.8. Determination of the optimal weight on the bit for drilling wellbore diameter of 165.1 mm.

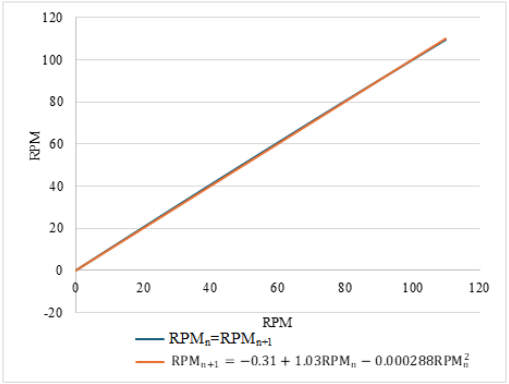

Fig.9. Relationship between RPM according to drilling rotor of bit 165.1 mm.

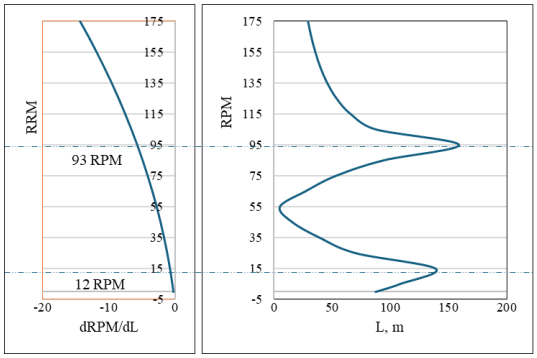

Fig.10. Determination of the optimal rotation per minute for drilling wellbore diameter of 165.1 mm.

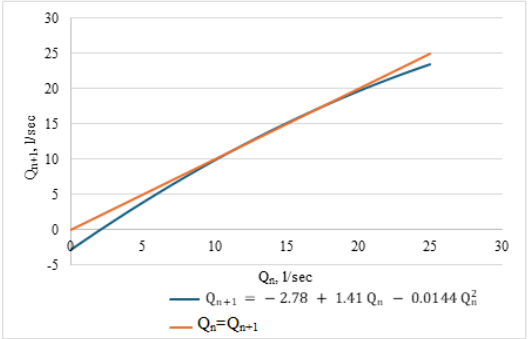

Fig. 11. Relationship between flow rate (Q) according to drilling mud motor of bit 165.1 mm.

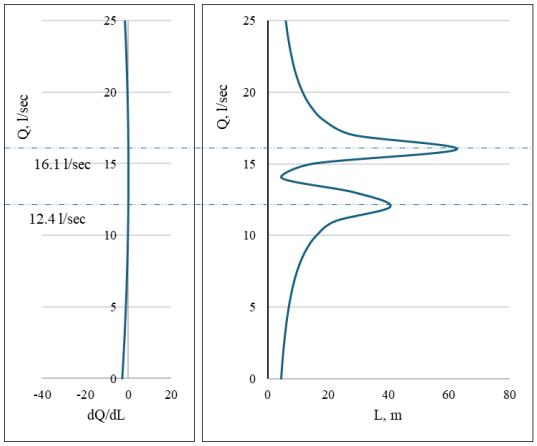

Fig.12. Determination of the optimal mud pump flow rate for drilling wellbore diameter of 165.1 mm.

Tab.1. Results of optimal drilling parameters based on the dynamic stability of the drill string of bit 165.1 mm.

Optimal drilling parameters for drilling wellbore diameter of 165.1 mm		
WOB_{op}, tons	RPM_{op}, rpm	Q_{op}, L/sec
4.65	93	16.1

The optimal value of WOB = 4.65 tons is determined because the first derivative is F'(WOB) = –0.04545 < 0. The optimal rotary speed is RPM = 93 rpm, with F'(RPM) = –0.023568 < 0. The optimal drilling fluid flow rate is Q = 17.4 L/s, with F'(Q) = –0.09112 < 0. All derivative values F'(WOB), F'(RPM), and F'(Q) are negative, ensuring that the drill string operates in a

stable condition. Based on the dynamic stability of the drill string condition, the drilling parameters were determined with significantly optimal drilling parameters for bits 165.1 mm to drill wells in the basement rock by drilling rotor. Optimal drilling parameter results have been applied to drill wellbore in the basement formation, which will ensure the stability of drilling parameters at the bottom hole and ensure the dynamic stability of the drill string system while drilling the wellbore diameter of 165.1 mm.

8 CONCLUSIONS

By applying the branch function, the study summaries in the following:

It is possible to study and evaluate the level of the dynamic stability of the drill string statement in the wellbore.

The degree of dynamic stability of the drill string analyzed allows to determine the drilling parameters to drill the wellbore diameter of 165.1 mm, which designs suitable the weight on the bit, mud pump flow rate, and rotation per minute.

Based on the level of dynamic stability of the drill string, engineer can design and select the most optimal drilling parameters to ensure that the dynamical drill string system works in the suitable wellbore diameter of 165.1 mm

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