OPTIMIZATION OF DRILLING PARAMETERS 
TO DRILL WELLS WITH HIGH DISPLACEMENT 
IN SOUTHERN CONTINENTAL SHELF OF VIETNAM 

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INTRODUCTION

1. Problem statement

Currently, drilling activities are very active in all Vietnam’s oilfields. Vietnam National Oil and Gas Group (PetroVietnam) planed to drill 65 to 75 new wellbores each year from now to 2015, which include exploration and production wells.

The majority of exploration and production wells in Vietnam are directional wells. With the increasing of measured depth, inclination angle, and horizontal departure, the dynamic system of Bottom hole Assembly (BHA) commonly becomes unstable. This decreases the productivity of drilling process.

To increase the drilling efficiency, we have to investigate the factors that affect to drilling process. The published researches mainly focused on the effect of individual parameter so the combination effect of all factors on dynamic drilling system has not been comprehensively investigated. In other words, evaluation of the effect of all factors to select optimized drilling parameters is practically important.

2. Objectives

Investigate the dynamic stability of the directional drilling process in Vietnam geological conditions focusing on White Tiger (Bach Ho) and Dragon (Rong) oilfields. This creates the fundamentals for drilling optimization to drill high displacement wellbores in Vietnam.

3. Scopes of the research

The scope of this research is the dynamics of drilling process, when drilling high displacement wellbores in Vietnam. In which, the controllable parameters, such as weight on bit, rotary speed, and flow rate for drilling inclined wellpaths, are investigated.

4. The research tasks

- Investigate the factors that affect on drilling efficiency;
- Apply the Catastrophe, Mapping and Mechanical specific energy theories to evaluate the efficiency of drilling dynamics of high displacement drilling operations in White Tiger and Dragon Oilfields. Also, select optimized drilling parameters for high displacement drillings.

5. Research methodology

- Statistical Method: Statistically collect and analyze the field data collected from high displacement wellbores drilled in White Tiger and Dragon Oilfields.

- Theoretical Method: Apply different theoretical methods to investigate the state the dynamic drilling system and evaluate the efficiency of the drilling process. This method is used to select optimized drilling parameters.

- Computer Applications: Various softwares and computer programs are used for data analysis.

6. The scientific and practical significance of the research

- Scientific significance: The application of Catastrophe and Mapping theories helps to evaluate the combination effect of all factors that affect the stability of dynamic drilling system. This research contributes to overcome the limitation of pervious methods, which focused on the effect of individual parameter;

- Practical significance: Selecting optimized drilling parameters based on dynamic stability and minimum mechanical specific energy enables us to reduce energy consumption, increase working time of drilling systems, and increase the penetration rate. Hence, this research helps to reduce the drilling cost and increase the productivity of drilling process.

7. The innovative aspects of the research

This research evaluated the combination effect of all factors on drilling efficiency.

The optimized drilling parameters have been selected based on the stability of dynamic drilling system and the minimum energy consumption
to crush the rock at the bottom of the wellbore.

8. The originality to be defended

- The granite basement condition in White Tiger and Dragon Oilfields are very complex for drilling process. During high displacement drilling operations, dynamic drilling system is always unstable and inefficient.

- Field data were analyzed to select the optimized drilling parameters. Drilling optimization based on dynamic stability and minimum specific energy consumption is practically important to increase the stability of drilling system and penetration rate. Hence, this helps to reduce drilling time and cost per meter.

9. The database of dissertation

This dissertation was written based on: Field data collected from drilling operations in White Tiger and Dragon Oilfields by Joint Venture Vietsovpetro (Vietsovpetro), Annual Reports of PetroVietnam, and published researches available in literature.

10. The dissertation layout

This dissertation includes the introduction, four chapters, conclusions, and recommendation. These are presented in 126 pages with 15 tables and 67 figures.

CHAPTER 1: OVERVIEW OF DRILLING EFFICIENCY

1.1. Criteria to evaluate the productivity of drilling process

Drilling efficiency can be evaluated based on two groups of criteria including quality and quantity criteria.

1.1.1. Quality criteria

These criteria include [6]:

- The deviation from the designed wellbore trajectory;

- Percentage and quantity (diameter, shape, original physical properties, components) of collected core samples;

- The ability to conduct well logging operations;

- The effect to oil and gas bearing formations.
1.1.2. Quantity criteria

1.1.2.1. Speed criteria

These criteria include [6]:

- **Penetration rate** \( v_{CH} \): The rate that the bit penetrates into the rock.
- **Round trip speed** \( v_H \): The length drilled within a round trip.
- **Technical speed** \( v_{KT} \): The utilizing efficiency of drill machine for a month.
- **Commercial speed** \( v_{TM} \): The efficiency of drilling activity, it defines the average drilled length per month created by the drilling equipment.
- **Cycle speed** \( v_{CT} \): The average depth per month created by the drilling equipment in the whole working cycle.

Speed criteria related tightly to each other as follows: \( v_{CH} > v_H > v_{KT} > v_{TM} > v_{CT} \). If one of certain speed increases, the next speed will also increase.

1.1.2.2. Cost per meter

Cost per meter is calculated as [6],

\[
C = \frac{C_{XL} + C_K}{L}, \text{ vnd/m} \tag{1.14}
\]

where, \( C_{XL} \) is other cost including well site preparation, transportation and construction, vnd; \( C_K \) is operating costs including drilling cost, wellbore stabilization cost, bit cost, drilling fluid cost, connection and tripping cost, vnd.

1.1.2.3. Energy for crushing rock

- **Mechanical specific energy** \( E_b, \text{ MPa} \): is the energy needed to break one unit volume of rock. It is also the ratio of consuming energy to the rate of penetration, and can be defined as [19, 34],

\[
E_b = 0.35 \left( \frac{0.04G}{\pi D^2} + \frac{4.8nM_x}{D^2 v_{CH}} \right) \tag{1.17}
\]

where, \( G \)- Weight on bit, kN; \( D \)- Bit diameter, cm; \( n \)- Rotary speed, rpm; \( M_x \)- Torque, N.m;
**b- Drill bit efficiency:** Drill bit efficiency is defined as [19]:

\[ e_f = \frac{\sigma_c}{E_b} \leq 1 \]  

where: \( \sigma_c \)- Unconfined compressive strength, Pa.

If \( e_f \) is approximately unity, the mechanical specific energy at the bit is low. Hence, drill bit efficiency is high.

### 1.2. Factors that affect the drilling efficiency

The factors that affect the drilling efficiency can be divided into two categories: uncontrollable factors and controllable factors. Uncontrollable factors are physical properties of rock at the bottom of the wellbore. Controllable factors are the factors that we can change during drilling process. These factors include weight on bit, rotary speed, drilling fluid parameters and drill bit type [8]. The stability of dynamic drilling system also has a significant effect on the drilling efficiency.

#### 1.2.1. The effect of weight on bit

In standard experiment conditions, the penetration rate is a function of weight on bit as [7]:

\[ v_{CH} = \Phi G^m \]  

##### (1.20)

#### 1.2.2. The effect of rotary speed

The penetration rate changes as a power function of rotary speed [7]:

\[ v_{CH} = \Phi_1 n^{m_0} , \; m_0 \geq 1 \]  

##### (1.21)

#### 1.2.3. Combination effect of weight on bit and rotary speed

The relationship among penetration rate, weight on bit and rotary speed can be described by following equation [7]:

\[ v_{CH} = \Phi_3 G^m n^{m_0} , \; m=1 \div 2; \; m_0=0,4 \div 1 \]  

##### (1.24)

#### 1.2.4. The effect of hydraulic parameters

**a- The effect of flow rate:** The relationship between rate of penetration and flow rate is:

\[ v_{CH} = \frac{Q}{a + b} \]  

##### (1.25)
where, $Q$ is flow rate, m$^3$/h; $a$, $b$ are constants depending on rock properties, weight on bit and rotary speed and structure of drill bits.

**b- The effect of jet velocity:** Penetration rate increases as jet velocity increase, even at the same flow rate. However, penetration rate increases slowly with the increasing of jet velocity as jet velocity is significantly high. Jet velocity has highest effect on penetration rate in the range of velocity from 70 to 100m/s.

**c- The combination effects of flow rate and jet velocity:** Penetration rate is proportional to $Qv_j^2$.

### 1.2.5. The effect of drilling fluid properties

All parameters including density, viscosity, filtration rate, and solid content have effect on penetration rate.

### 1.2.6. The effect of rock properties

Penetration rate is inversely proportional to the hardness of rock as

$$v_{CH} \sim \frac{1}{\sigma}$$

where, $\sigma$ is the hardness of the rock at the bottom of the wellbore, Pa.

The abrasiveness of rocks has a strong effect on the working time of drill string and bottom hole assembly and drill bit. The compressive strength of the rock is closely related to wellbore stability.

### 1.2.7. The effect of the stability of dynamic drilling system

#### 1.2.7.1. The effect of vibration

Three main types of vibration are axial vibration, lateral vibration, and Torsional - twisting vibration [25].

**a- Axial vibration:** This vibration is the result of the change in axial force, circulation pressure and the interaction between drill bit and rock. It decreases the working time of drill bit on the bottom of the wellbore, hence, decreases the penetration rate.

**b- Lateral vibration:** This vibration increases the diameter of the wellbore and decreases the penetration rate.

**c- Torsional - twisting vibration:** This vibration is the result of the
stick-slip between drill string and wellbore. It often leads to fatigue breakage, bit and drill string wear. Therefore, it decreases drilling efficiency.

All vibrations can appear simultaneously. The combination of these vibrations may create a severe combination effect.

1.2.7.2. Factors create instability of dynamic drilling system

These factors include drilling parameters, especially weight on bit and rotary speed, drilling methods, surface and bottom hole equipments, wellbore trajectory, wellbore diameter, and operational conditions.

1.3. Conclusions

Penetration rate is the first criterion to evaluate the drilling efficiency. High penetration rate reduces the cost per meter. Cost per meter is the overall evaluation criterion to evaluate the drilling productivity.

In drilling operations, criteria related to drill bit are highly important and have strong effects on other criteria.

Stability of dynamic drilling system in drilling process has a strong effect on drilling efficiency. Drilling parameters are controllable parameters and have significant influence on drilling efficient criteria. Hence, selecting optimized drilling parameters is the key to success in drilling operations.

CHAPTER 2: DRILLING ACTIVITY IN VIETNAM

2.1. Oil-bearing Formation

Nearly all oil and gas formations in Vietnam are in Tertiary basin. Many producing oilfields such as White Tiger, Dragon, Rang Dong, Ruby, and Black Lion are in Cuu Long Basin, the highest oil reserve basin in Vietnam. White Tiger is a largest and first discovered oilfield in Vietnam. Its oil bearing formation is the fractured basement reservoir, which is a very special oil reservoir in the world [10].
The development history of Cuu Long Basin is closely related to the history of Vietnam’s petroleum industry. White Tiger Oilfield has all properties of this basin.

2.1.1. **Stratigraphy of White Tiger Oilfield**

Geological stratigraphic column of the White Tiger field consists of Pre-Kainozoic crystalline basement and sedimentary rocks. The total thickness of the basement rock is 1990m and that of the sedimentary rock is 4740m.

The basement rock consists of crystallized magmatic granitoid, basalt-andesite, and poocfia diaba of Jura. The hardness of these rocks is from 20 MPa to 30MPa. Based on GOST-122-88-66 scale, these rocks have the hardness of VII [9].

Kainozoic sediments are divided into six sub-formations from the Oligocene to Quaternary.

2.1.2. **Oil-bearing formation in White Tiger Oilfield**

The main oil-bearing formation in White Tiger oilfield is fractured basement. The remainder is from Oligocene and Lower Miocene reservoirs with small reserve and complex geological conditions.

The total thickness of the oil-bearing formations in this oilfield is 2150m from the basement to Miocene reservoirs, in which 126 oil-bearing formations have been discovered. The oil-bearing formations in sedimentary rocks have low reserve, and their thickness varies from 15m to 800m. The thickness of the oil-bearing formation in basement is approximately 1800m.

2.2. **Field development history**

Before Liberation of Saigon, the exploration activities were conducted by international companies such as Exxon Mobil, Pecten, and Union Texas.

After Liberation of Saigon, the exploration activities had significant change started with the foundation of Vietnam General Directorate of Oil
and Gas which is now named as Vietnam National Oil and Gas Group. Field surveys and explorations were conducted mainly by AGIP (Italia), Meminex (Germany), and Bowvalley (Canada).

The milestone in the development of Vietnam’s Petroleum industry is the foundation of Joint Venture Vietsovpetro in 1981. In 1986, the first oil-bearing formation was discovered in Miocene rock of White Tiger Oilfield. Two years later, 1988, oil was discovered in fractured basement.

According to PetroVietnam, the number of new wells drilled every year is continuously increased. These new wells are mainly located on Cuu Long and Nam Con Son basins.

2.3. Wellbore trajectory and casing diagram

2.3.1. Wellbore trajectory

Almost all drilled wellbores have S-shape and J-shape trajectories. Other trajectories are also used. However, these trajectories are similar to S-shaped or J-shaped trajectories except for the horizontal section.

2.3.2. Casing diagram

The casing diagrams used in Cuu Long Basin are very complex with different casing diameters including 508, 340, 245, 194, 178mm.

In White Tiger and Dragon Oilfields, wellbore sections in basement rocks are uncased. The intermediate casing with diameter of 245mm is often run to the top of basement rock. Depending on the wellbore’s location, the bit diameter of 215.9mm or 165.1mm is often used to drill the next sections.

2.4. Displacement of wellbore

Displacement of wellbore is the horizontal distance between the surface location and the point on the wellbore trajectory. The displacement of wellbore is increased year after year with the development of new techniques and drilling equipments. Currently, the displacement of wellbores in Vietnam is commonly smaller than 2500m. Hence, wellbores
with displacement higher than 1000m can be classified as high displacement wellbores.

2.5. Characteristics of drilling operations in White Tiger and Dragon Oilfields

The drill bits used in White Tiger and Dragon Oilfields are mainly roller cone and diamond drill bits supplied by Baker Hughes, Reed, Smith, Security, Varel, HTC, Hycalog, and British Bits.

The drilling parameters for different drill bit diameters are presented in Table 2.1.

<table>
<thead>
<tr>
<th>Diameter [mm]</th>
<th>Bit type</th>
<th>G [kN]</th>
<th>n [rpm]</th>
<th>Q [m³/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>660.4</td>
<td>Roller Cone</td>
<td>20 - 60</td>
<td>70 - 110</td>
<td>180 - 230</td>
</tr>
<tr>
<td>444.5</td>
<td>Roller Cone</td>
<td>60 - 140</td>
<td>75 - 170</td>
<td>180 - 220</td>
</tr>
<tr>
<td></td>
<td>Diamond</td>
<td>10 - 50</td>
<td>130 - 170</td>
<td>240 - 320</td>
</tr>
<tr>
<td>311.1</td>
<td>Roller Cone</td>
<td>100 - 180</td>
<td>110 - 150</td>
<td>120 - 170</td>
</tr>
<tr>
<td></td>
<td>Diamond</td>
<td>50 - 100</td>
<td>90 - 170</td>
<td>200 - 260</td>
</tr>
<tr>
<td>215.9</td>
<td>Roller Cone</td>
<td>100 - 250</td>
<td>90 - 180</td>
<td>120 - 140</td>
</tr>
<tr>
<td>165.1</td>
<td>Roller Cone</td>
<td>40 - 130</td>
<td>70 - 90</td>
<td>90 - 120</td>
</tr>
</tbody>
</table>

The drilling fluid systems used for different depth are: High viscosity drilling fluids brine/CMC/Bentonite system, Gel/KCl/PHPA system, KCl/PHPA/Polymer system, Glycol/KCl/PHPA system; and synthetic oil-based drilling fluids.

2.6. Conclusions

Cuu Long Basin has highest oil reserve in Vietnam. In Cuu Long Basin, White Tiger is the largest oilfield. The oil-bearing formation in this oilfield is a typical type of fractured basement reservoir in Vietnam and in the world.

The wellbore sections in the basement of White Tiger and Dragon oilfields were drilled by 215.9mm and 165.1mm drill bits. The wellpath drilled by these drill bits commonly have high horizontal departure.
CHAPTER 3: STABILITY EVALUATION OF DYNAMIC DRILLING SYSTEM FROM DRILLING MODEL

3.1. The operation characteristic of dynamic drilling System

While working at the bottom of the wellbore, drill bit is under the effect of different forces. These forces may eliminate each other or may generate a combination effect. Wellbore and rock are a closed dynamic system. The working of drill bit to break the rock at the bottom of the wellbore is controlled by drilling parameters.

The working of drill bit is very complex. In drilling operations, we wish to know if the dynamic system of wellbore and rock is stable or unstable and we also need to evaluate how stable this dynamic system is.

3.2. The stability of dynamic drilling system during drilling process

3.2.1. Theoretical study

a- Catastrophe theory: The Catastrophe theory is known as the heterogeneous change, which appears on sudden state of research system in the regular change of boundary conditions.

The mathematical model for a dynamic system can be described by a differential equation as

\[
\frac{dx}{dt} = f(x, c_1, c_2, \ldots, c_n)
\] (3.1)

where, \( f \) is function of the function of state \( x \), and other controllable parameters \( c_1, c_2, \ldots, c_n \). The boundary conditions are:

\[
\left( \frac{df}{dx} \right)_u = 0; \quad \left( \frac{d^2f}{dx^2} \right)_u > 0
\] (3.2)

These boundary conditions are required for the stability of the dynamic system.

b- Mapping theory: Non-linear phenomena can be investigated by utilizing bifurcation function of mapping theory as

\[
x_{n+1} = rx_n (1 - x_n)
\] (3.3)
where, \( r \) is a controlled parameter; \( x_n \) is a function described the relationship between two successive variables.

The properties of bifurcation function are the key to study non-linear phenomena.

3.2.2. Stability evaluation of dynamic drilling system

\textbf{a- Applying Catastrophe theory:} The working of the drill bit to break the rock at the bottom of the wellbore can be modeled by Eq. 3.4.

\[
\frac{dv_{CH}}{dt} = c_1 v_{CH}^2 + c_2 v_{CH} + c_3
\]  

(3.4)

where, \( t \) is time required to drill one meter; parameters, \( c_1, c_2, \) and \( c_3 \) are controlled parameters characterized the effect of geological conditions, drilling fluid, bottom hole assembly, measured depth, wellbore trajectory, and drilling parameters. These parameters are determined from field data analysis. These field data, including drilling parameters for each measured depth, were collected from high displacement drilling operations in White Tiger and Dragon oilfields.

We define coefficient, \( \Delta \), as: 
\[
\Delta = c_2^2 - 4c_1c_3
\]

- If \( \Delta > 0 \), dynamic drilling system is stable;
- If \( \Delta < 0 \), dynamic drilling system is unstable;
- \( \Delta = 0 \) is the boundary between stable and unstable. This is critical condition since the dynamic system may easily to be unstable.

\textbf{b- Applying Mapping theory:} When using bifurcation function Eq. 3.3 to model the working of drill bit, Eq 3.3 has the new form:

\[
v_{CH(n+1)} = rv_{CH(n)} \left( 1 - \frac{v_{CH(n)}}{v_{CH_{max}}} \right)
\]  

(3.5)

where, \( v_{CH(n)} \) is penetration rate at the measured depth of \( n \), \( r \) is a controlled parameter similar to \( c_1, c_2, \) and \( c_3 \). This parameter is obtained from field data analysis.

- If \( 0 < r \leq 1 \), dynamic drilling system is stable and the working of drill bit is also stable;
- If $1<r\leq 3$, dynamic drilling system is in transition state and may change from stable to unstable;
- If $3<r\leq 3,45$, dynamic drilling system is unstable.

Collected field data from high displacement wellbores drilled in White Tiger and Dragon Oilfields are analyzed. Equations 3.4 and 3.5 are used to determine $\Delta$ and $r$ for each measured depth. Data analysis confirms that at some measured depths: $\Delta \approx 0$ and $r \approx 1$. These show that dynamic drilling system is in transition state and can easily be unstable. This transition state is commonly encountered in Oligocene rock and basement rock ($\Delta \approx 0$, $r>1$). Under this condition, drill bit and dynamic drilling system are unstable. Hence, this leads to low penetration rate or low drilling productivity. We can conclude that drilling parameters have not been selected properly.

### 3.3. Evaluation of drilling efficiency in the basement of White Tiger and Dragon oilfields

#### 3.3.1. Bit mechanic

To use the specific energy as a criterion to evaluate drilling efficiency, we need to investigate the bit mechanic as shown in Fig. 3.15 [19].

![Diagram of penetration rate vs. weight on bit](image)

**Figure 3.15**: Relationship between Penetration rate and Weight on bit

- Region I: Drilling efficiency and the penetration rate are constrained by inadequate depth of bit cutters due to low weight on bit.
- Region II: This region starts when the depth of cut becomes adequate for the bit's performance to stabilize. Throughout this region, the penetration rate is linearly proportional to weight on bit. Though the bit efficiency is not changing, a greater amount of energy is being applied so the penetration rate increases proportionally.

- Region III: This region starts at the founder point where a condition develops in which the transfer of energy from the bit to the rock is constrained due to the effects of hydraulic and mechanical factors.

3.3.2. Drilling efficiency in basement rock

As presented in section 3.2, in this section, we will investigate the application of mechanical specific energy to evaluate the drilling efficiency in basement rock for high displacement drilling in White Tiger and Dragon Oilfields. Equation 1.17 and 1.18 will be used for analysis. To evaluate drilling efficiency, we can use two methods:

- Analyze the change of mechanical specific energy, $E_b$;
- Compare mechanical specific energy, $E_b$, with unconfined compressive strength, $\sigma_c$.

Data analysis shows that the mechanical specific energy at the drill bit is too high compared to the unconfined compressive strength of the basement rocks ($\sigma_c > 190$MPa). This means that $e_f$ is very smaller than one; the bit is working on region III. The reason for this was discussed in details in section 3.2.

3.4. Conclusions

We can conclude that the stability of dynamic drilling system when drilling in the basement rocks of White Tiger and Dragon oilfields is weak. This leads to low drilling productivity. To increase the drilling efficiency, some changes in equipment and drilling parameters are required. Drilling parameters are controllable parameters and can directly stabilize the dynamic drilling system.
CHAPTER 4: OPTIMIZATION OF DRILLING PARAMETERS FOR THE BASEMENT ROCK OF WHITE TIGER AND DRAGON OILFIELDS

4.1. Optimization Methods

In the published literature, many methods have been proposed to select optimized drilling parameters. However, these methods are not based on the real working condition of dynamic drilling system and energy for rock breakage. Also, they did not count for the combination effects of different factors on the working of the drill bit in the wellbore.

4.2. Selecting optimized drilling parameters for basement rock

4.2.1. Selecting optimized drilling parameters based on mechanical specific energy

Drilling parameters are selected to achieve low specific energy at the drill bit and close to the compressive strength of basement rock. To obtain equation 1.17 as a function of G and n, the torque can be obtained from Iogancen’s model [38]:

\[ M_x = M_o + \frac{BD^2(Kn - U)G}{n^{1.5}} \]  \hspace{1cm} (4.1)

where, the torque, \( M_o \), does not depend on weight on bit; Coefficient, B, depends on drill bit parameters (D=215.9mm, B=0.28; D<215.9mm, B=0.33); Coefficient, K, depends on rock properties; Coefficient, U, depends on rotary speed.

The rate of penetration can be calculated from Fedorov’s model [40]:

\[ v_{CH} = aG^b n^c \]  \hspace{1cm} (4.2)

Substitute Equation 4.1 and Equation 4.2 into mechanical specific energy equation we obtain:

- For drill bit 215.9mm:

\[ E_b = \frac{10,29.10^{-3}M_o}{a} G^{-b} n^{1-c} + \frac{1,344K}{a} G^{1-b} n^{0.5-c} - \frac{1,344U}{a} G^{1-b} n^{-0.5-c} + 2.73.10^{-5} G \]  \hspace{1cm} (4.3a)

- For drill bit 165.1mm:
\[ E_b = \frac{17.61 \times 10^{-3} M_o}{a} G^{-b} n^{1-c} + \frac{1.584 K}{a} G^{1-b} n^{0.5-c} - \frac{1.584 U}{a} G^{1-b} n^{-0.5-c} + 4.67 \times 10^{-5} G \quad (4.3b) \]

where \( a, b, c \) are coefficients characterized geological condition, inclination angle, true vertical depth, measured depth, horizontal departure. Parameters, \( a, b, c, M_o, K, \) and \( U \) are determined from field data collected from high displacement drilling operations in White Tiger and Dragon Oilfields. The result is summarized in Table 4.1.

Table 4.1: Parameters \( a, b, c, M_o, K, \) and \( U \) for two drill bit diameters

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Bit diameter, [mm]</th>
<th>215.9</th>
<th>165.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a )</td>
<td>( 6.33 \times 10^{-3} )</td>
<td>1.01 \times 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>( b )</td>
<td>0.227</td>
<td>0.408</td>
<td></td>
</tr>
<tr>
<td>( c )</td>
<td>1.235</td>
<td>1.399</td>
<td></td>
</tr>
<tr>
<td>( M_o )</td>
<td>65957</td>
<td>11237</td>
<td></td>
</tr>
<tr>
<td>( K )</td>
<td>23</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>( U )</td>
<td>1136</td>
<td>1388</td>
<td></td>
</tr>
</tbody>
</table>

Substituting the parameters from Table 4.1 in to equation 4.2, equation 4.3a, and equation 4.3b, we obtained the result as shown in Figure 4.1 - 4.4 and the drilling parameters as presented in Table 4.2.

Figure 4.1: The variation of \( E_b, v_{CH} \) with \( G \) for drill bit 215.9mm when drilling with mud motor
Figure 4.2: The variation of $E_b$, $v_{CH}$ with $G$ for drill bit 215.9mm when drilling with rotary table

Figure 4.3: The variation of $E_b$, $v_{CH}$ with $G$ for drill bit 165.1mm when drilling with mud motor

Figure 4.4: The variation of $E_b$, $v_{CH}$ with $G$ for drill bit 165.1mm when drilling with rotary table
4.2.2. Selecting drilling parameters based on dynamic stability

4.2.2.1. Selecting model to determine the drilling parameters

Non-linear model for weight on bit:

\[
\frac{dG}{dL} = F(G) = rG \left( \frac{G_{\text{max}} - G}{G_{\text{max}}} \right) - G_0
\]  

(4.9)

where, \(G_{\text{max}}\) is Maximum weight on bit, kN; \(r\) is controlled parameters; \(G_0\) is the reduction of weight due to friction and axial vibration.

Simplifying equation 4.9 we obtain a function of three controlled empirical parameters:

\[G_{n+1} = a_1 G_n - b_1 G_n^2 - Z_1\]  

(4.13a)

Similarly, by simplifying the equation for rotary speed and flow rate, we obtain:

\[n_{n+1} = a_2 n_n - b_2 n_n^2 - Z_2\]  

(4.13b)

\[Q_{n+1} = a_3 Q_n - b_3 Q_n^2 - Z_3\]  

(4.13c)

4.2.2.2. Determination of model parameters

From field Data analysis for extended-rearch wellbores in White Tiger and Dragon Oilfields, we obtain following empirical equation for drilling parameters:

**a- Drill bit 215.9mm:**

- Mud motor:
\[ G_{n+1} = 1.175G_n - 0.0011G_n^2 - 3.0108 \]  \hspace{1cm} (4.14)

\[ n_{n+1} = 0.9894n_n + 0.00035n_n^2 + 0.0321 \]  \hspace{1cm} (4.15)

\[ Q_{n+1} = 1.0171Q_n - 1.2815Q_n^2 + 0.0011 \]  \hspace{1cm} (4.16)

- **Rotary table:**

\[ G_{n+1} = 0.8506G_n + 0.000219G_n^2 + 20.261 \]  \hspace{1cm} (4.17)

\[ n_{n+1} = 0.0744n_n + 0.311n_n^2 + 0.658 \]  \hspace{1cm} (4.18)

\[ Q_{n+1} = 9215Q_n - 0.182Q_n^2 + 0.00201 \]  \hspace{1cm} (4.19)

**b- Drill bit 165.1mm:**

- **Mud motor:**

\[ G_{n+1} = 1.012G_n - 0.00113G_n^2 + 1.986 \]  \hspace{1cm} (4.20)

\[ n_{n+1} = 1.589n_n - 0.109n_n^2 - 0.774 \]  \hspace{1cm} (4.21)

- **Rotary table:**

\[ G_{n+1} = 1.205G_n - 0.0016G_n^2 - 2.937 \]  \hspace{1cm} (4.22)

\[ n_{n+1} = 1.357n_n - 0.187n_n^2 - 0.165 \]  \hspace{1cm} (4.23)

4.2.2.3. **Selecting drilling parameters for drilling in basement rock**

To obtain a stable dynamic system, following conditions must be satisfied:

\[ G_{n+1} = G_n ; \quad n_{n+1} = n_n ; \quad Q_{n+1} = Q_n \]

Equations 4.14 to 4.23 can be rewritten in the form:

**a- For drill bit 215.9mm:**

- **Mud motor:**

\[ \frac{dG}{dL} = 0.175G_n - 0.0011G_n^2 - 3.0108 \]  \hspace{1cm} (4.24)

\[ \frac{dn}{dL} = -0.011n_n + 0.00035n_n^2 + 0.0321 \]  \hspace{1cm} (4.25)

\[ \frac{dQ}{dL} = 0.017Q_n - 1.2815Q_n^2 + 0.0011 \]  \hspace{1cm} (4.26)
- Rotary table:

\[
\frac{dG}{dL} = -0.149G_n + 0.000219G_n^2 + 20.261
\]  

(4.27)

\[
\frac{dn}{dL} = -0.926n_n + 0.314n_n^2 + 0.658
\]  

(4.28)

\[
\frac{dQ}{dL} = -0.079Q_n - 0.182Q_n^2 + 0.00201
\]  

(4.29)

- Mud motor:

\[
\frac{dG}{dL} = 0.012G_n - 0.00113G_n^2 + 1.986
\]  

(4.30)

\[
\frac{dn}{dL} = 0.589n_n - 0.109n_n^2 - 0.774
\]  

(4.31)

- Rotary table:

\[
\frac{dG}{dL} = 0.205G_n - 0.0016G_n^2 - 2.937
\]  

(4.32)

\[
\frac{dn}{dL} = 0.357n_n - 0.187n_n^2 - 0.165
\]  

(4.33)

Based on equations 4.24 to 4.33 and field date, we obtain the drilling parameters for high displacement drilling in White Tiger and Dragon Oilfields. These parameters are presented in Table 4.3.

Table 4.3: Selected drilling parameters based on dynamic stability

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Drilling Parameters</th>
<th>Optimized Drilling Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>G, [kN]</td>
<td>n, [rpm]</td>
</tr>
<tr>
<td>Drill bit 215.9mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mud motor</td>
<td>80 - 160</td>
<td>160 - 250</td>
</tr>
<tr>
<td>Rotary table</td>
<td>150 - 250</td>
<td>60 - 90</td>
</tr>
<tr>
<td>Drill bit 165.1mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mud motor</td>
<td>40 - 80</td>
<td>150 - 210</td>
</tr>
<tr>
<td>Rotary table</td>
<td>70 - 140</td>
<td>50 - 80</td>
</tr>
</tbody>
</table>
From the drilling parameters presented in 4.2 and 4.3, we obtain the drilling parameter for two drill bit diameters 215.9mm and 165.1mm. These parameters are presented in Table 4.4.

Table 4.4: Selected drilling parameters for the basement rock of White Tiger and Dragon oilfield

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Suitable Drilling Parameters</th>
<th>Optimized Drilling Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>G, [kN]</td>
<td>n, [rpm]</td>
</tr>
<tr>
<td>Drill Bit 215,9mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mud Motor</td>
<td>100 - 150</td>
<td>200 - 230</td>
</tr>
<tr>
<td>Rotary Table</td>
<td>160 - 230</td>
<td>65 - 85</td>
</tr>
</tbody>
</table>

4.3. Field application result

The drilling parameters which selected above were applied to drill intervals in basement rock of wells 404 RCDM and 421 RC-4. The field drilling results of these wells were compared with the one of well 465 BK-8. These results are presented in Table 4.5.

- Base on rate of penetration: The average penetration rate of well 404 RCDM increased $\frac{7.75}{5.16} \times 100 \approx 50\%$ comparing with well 465 BK-8; the average penetration rate of well 404 RCDM increased $\frac{7.03}{5.16} \times 100 \approx 36\%$ comparing with well 465 BK-8.

- Base on cost per meter: The consumption of the bit for well 465 BK-8 was two more compared with wells 404 RCDM and 421 RC-4. This leads to the more time requiring for tripping in and tripping out of well 465 BK-8. If the cost per meter is determined by Equation 1.14, the cost per meter of wells 404 RCDM and 421 RC-4 are less than well 465 BK-8.
<table>
<thead>
<tr>
<th>Well Name: 404 RCDM, Used new drilling parameters</th>
<th>Measured depth, m</th>
<th>Length, [m]</th>
<th>Number of drill bit</th>
<th>Penetration rate, [m/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3978</td>
<td>4011</td>
<td>33</td>
<td>1</td>
<td>2.6</td>
</tr>
<tr>
<td>4011</td>
<td>4144</td>
<td>133</td>
<td>1</td>
<td>4.9</td>
</tr>
<tr>
<td>4144</td>
<td>4351</td>
<td>207</td>
<td>1</td>
<td>5.9</td>
</tr>
<tr>
<td>4351</td>
<td>4430</td>
<td>79</td>
<td>1</td>
<td>5.9</td>
</tr>
<tr>
<td>4430</td>
<td>4735</td>
<td>305</td>
<td>1</td>
<td>11.0</td>
</tr>
<tr>
<td>4735</td>
<td>4858</td>
<td>123</td>
<td>1</td>
<td>16.2</td>
</tr>
<tr>
<td>3978</td>
<td>4858</td>
<td>880</td>
<td>6</td>
<td>7.75</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Well Name: 421 RC-4, Used new drilling parameters</th>
<th>Measured depth, m</th>
<th>Length, [m]</th>
<th>Number of drill bit</th>
<th>Penetration rate, [m/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3935</td>
<td>4031</td>
<td>96</td>
<td>1</td>
<td>7.6</td>
</tr>
<tr>
<td>4031</td>
<td>4138</td>
<td>107</td>
<td>1</td>
<td>6.8</td>
</tr>
<tr>
<td>4138</td>
<td>4290</td>
<td>152</td>
<td>1</td>
<td>6.3</td>
</tr>
<tr>
<td>4290</td>
<td>4453</td>
<td>163</td>
<td>1</td>
<td>6.0</td>
</tr>
<tr>
<td>4453</td>
<td>4640</td>
<td>187</td>
<td>1</td>
<td>6.9</td>
</tr>
<tr>
<td>4640</td>
<td>4765</td>
<td>125</td>
<td>1</td>
<td>8.6</td>
</tr>
<tr>
<td>3935</td>
<td>4765</td>
<td>830</td>
<td>6</td>
<td>7.03</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Well Name: 465 BK-8, Used old drilling parameters</th>
<th>Measured depth, m</th>
<th>Length, [m]</th>
<th>Number of drill bit</th>
<th>Penetration rate, [m/h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3948</td>
<td>3989</td>
<td>41</td>
<td>1</td>
<td>8.2</td>
</tr>
<tr>
<td>3989</td>
<td>4109</td>
<td>120</td>
<td>1</td>
<td>4.9</td>
</tr>
<tr>
<td>4109</td>
<td>4142</td>
<td>33</td>
<td>1</td>
<td>4.5</td>
</tr>
<tr>
<td>4142</td>
<td>4268</td>
<td>126</td>
<td>1</td>
<td>4.4</td>
</tr>
<tr>
<td>4268</td>
<td>4362</td>
<td>94</td>
<td>1</td>
<td>7.8</td>
</tr>
<tr>
<td>4362</td>
<td>4461</td>
<td>99</td>
<td>1</td>
<td>3.6</td>
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<tr>
<td>4461</td>
<td>4691</td>
<td>230</td>
<td>1</td>
<td>3.7</td>
</tr>
<tr>
<td>4691</td>
<td>4791</td>
<td>100</td>
<td>1</td>
<td>4.2</td>
</tr>
<tr>
<td>3948</td>
<td>4791</td>
<td>843</td>
<td>8</td>
<td>5.16</td>
</tr>
</tbody>
</table>
CONCLUSIONS

The Catastrophe theory and Bifurcation function are highly important to investigate the dynamic stability of drilling operations. The results of this study provide us the measured depth ranges that the dynamic drilling system will be unstable due to improper selection of drilling parameters. Hence, it is practically important in drilling optimization.

The results show a good agreement between two theories. The results were also validated by the minimum mechanical specific energy principle.

The dynamic drilling system, high displacement drilling in basement rock of White Tiger Oilfield, is unstable. This is the main reason for low drilling productivity.

Based on principle of mechanical specific energy and dynamic stability, we obtain the optimized drilling parameters for high displacement drilling in basement rock of White Tiger and Dragon Oilfields. Application of these parameters, as presented in Table 4.4, helps to increase the stability of dynamic drilling system and the rate of penetration. Therefore, this reduces the cost per meter.
RECOMMENDATIONS

The result of this study should be applied in drilling operations for basement rocks in Vietnam.

It is recommended to subdivide the basement into sublayers based on the physical property, and optimize the drilling parameters for each sublayer. This enables us to select more proper drilling parameters.

Mechanical specific energy principle is highly important theory for drilling optimization. This help to evaluate the efficiency of drilling operations and also it shows us the reason for low drilling efficiency. Therefore, extensive investigation and application of this theory are recommended for the future researches and field operations in Vietnam.
AUTHOR'S PUBLICATION


