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Chapter 7

Drilling Performance Optimization Based on Mechanical Specific Energy Technologies

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Additional information is available at the end of the chapter

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Abstract

Mechanical specific energy (MSE) has been widely used to quantify drilling efficiency and maximize rate of penetration (ROP) in oil and gas wells drilling. In this chapter, MSE models respectively for directional or horizontal drilling and rotating drilling with positive displacement motor (PDM) are established based on the evaluation of virtues and defects of available MSE models. Meanwhile methods for drilling performance prediction and optimization based on MSE technologies are presented. Field data presented in this chapter indicates that the developed MSE models estimate MSE values with a reasonable approximation in the absence of reliable torque measurements, the method for optimizing drilling parameters can estimate optimum WOB values with different RPM to drill a specific formation interval with PDM. It also show that the optimum WOB is low for rotating drilling with PDM compared with the conventional drilling without PDM, increasing WOB does not always increase ROP but is more likely to decrease ROP. The drilling performance prediction and optimization methods based on MSE technologies could be effectively used to maximize ROP and allow operators to drill longer and avoid unnecessary trips, and is worthy to be applied and promoted with highly diagnostic accuracy, effective optimizing and simple operation.

Keywords: mechanical specific energy, drilling performance optimization, positive displacement motor, optimum WOB, maximize rate of penetration

1. Introduction

Maximizing ROP to reduce drilling cost in oil and gas development is the permanent objective of drilling researchers [1–4]. Numerous methods have been developed for optimizing drilling parameters to maximize ROP, and they are similar to drill rate and drill-off tests in that they observe trends in performance and attempt to identify the founder point, which is the point at

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which the ROP is maximized [5]. Although these methods have enhanced drilling performance, they do not provide an objective assessment of the true potential ROP, only the founder point of the current system. Actually the process of optimizing drilling parameters should be not only drilling system specific but also formation specific. MSE is defined as the mechanical work done to excavate a unit volume of rock, it could provide an objective assessment of the drilling efficiency and an objective tool to identify the bit founder. The initial MSE model for rotating drilling system was proposed by Teale in 1965 [6]. In this model, as the majority of field data is in the form of surface measurements, which results in MSE's calculation containing even large sources of error. Then numerous investigators were motivated to develop more accurate models. These models include those presented by Pessier and Fear [7], Dupriest and Koeteritz [5], Armenta [8], Mohan et al. [9], Cherif [10], Mohan et al. [11] and they have been widely used in bit selection, drilling efficiency quantification, drilling performance monitoring, drilling performance optimization, ROP improvement and so on. Although the MSE obtained from these models are more and more precisely model the actual downhole drilling in vertical wells, currently there are few effective MSE models to precisely model the actual downhole drilling in directional or horizontal wells due to the majority of field data is in the form of surface measurements.

Moreover, in recent years, PDM has gained widespread use in the hard formation drilling to improve ROP. In rotating drilling with PDM, the power section of PDM converts hydraulic energy of mud flow into mechanical rotary power, the surface rotation is superimposed on downhole motor rotation. During slide drilling, bit rotation is generated only from the PDM as drilling fluid is pumped through the drill string. However, the PDM's performance is controlled by the combination of the rotor/stator lobe configuration, and the direct measurement of PDM rotary speed and torque in down hole has proven difficult. Therefore, currently there are also few effective MSE models to precisely model the actual downhole drilling for rotating drilling with PDM.

In this chapter, MSE models respectively for directional or horizontal drilling and rotating drilling with PDM are established based on the evaluation of key MSE models and the analysis on PDM performance, meanwhile methods for drilling performance prediction and optimization based on MSE technologies are presented.

2. Mechanical specific energy model development

2.1. Key models of mechanical specific energy

Mechanical specific energy (MSE) has been defined as the mechanical work done to excavate a unit volume of rock. Teale in 1965 initially proposed the MSE model for rotating drilling system [6].

$$MSE = \frac{WOB}{A_b} + \frac{120\pi \cdot RPM \cdot T}{A_b \cdot ROP} \tag{1}$$

In the above model, torque at the bit is a main variable. Although torque at the bit can be easily measured in the laboratory and with Measurement While Drilling (MWD) systems in the field, the majority of field data is in the form of surface measurement. While in the absence of reliable torque at the bit measurements, the calculation of MSE based on this model contains even large sources of error. Therefore, it is only used qualitatively as a trending tool.

In 1992, Pessier and Fear provided a simple method of the calculation of torque at bit while in the absence of reliable torque measurements and optimized Teale's model [7].

$$MSE = WOB \cdot \left(\frac{1}{A_b} + \frac{13.33 \cdot \mu_b \cdot RPM}{D_b \cdot ROP}\right)$$
$$\mu_b = 36\frac{T}{D_b \cdot WOB} \tag{2}$$

The above model's parameters are easy to be obtained on the ground, and its calculation precision has been improved, as a result, it has a common usage in the drilling industry. In this model, the torque of bit is calculated through WOB. However, WOB is always read based on the surface measurement, which is not the bottom hole real WOB. As for directional and horizontal drilling, there is a great difference between the bottom hole real WOB and the WOB of surface measurement [12]. And every bit has a certain mechanical efficiency in drilling even for the new bits, thus Pisser's model has a limited application and also exists a certain error in MSE calculation.

Given the bit had a certain mechanical efficiency in the actual drilling process, Dupriest, Cherif and Amadi defined a mechanical efficiency on the base of Teale model [5, 10, 13].

$$MSE = E_m \cdot \left(\frac{WOB}{A_b} + \frac{120 \cdot \pi \cdot RPM \cdot T}{A_b \cdot ROP}\right) \tag{3}$$

Dupriest and Koederitz thought peak bit efficiencies are always in the 30–40% range, therefore thought the mechanical efficiency were 35% [5]. However, this is a controversial issue due to the bits' mechanical efficiency depending on a variety of factors, and it may vary greatly from the assumed 35%. Cherif argued that the mechanical efficiency were 26–64% instead of 35% [10]. In directional and horizontal drilling, the MSE values may eventually become several times the formation CCS due to torsional friction. So Amadi and Iyalla thought the mechanical efficiency were 12.5% in directional and horizontal drilling [13]. Actually the mechanical efficiency is not only bit specific but also formation specific, and it may vary greatly from bit to bit and formation to formation, so it must be determined according to the real drilling conditions. Therefore, the model also has certain limitations.

Recently some researchers think that hydraulic energy also aids in actual drilling for certain formations, then they add the hydraulic term to the MSE function as [9, 11].

$$MSE = \frac{WOB}{A_b} + \frac{120\pi \cdot RPM \cdot T}{A_b \cdot ROP} + \frac{\beta \cdot \Delta P_b \cdot Q}{A_b \cdot ROP} \tag{4}$$

Hydraulic energy has a great influence on drilling efficiency, but its role is complex. In conventional rotating drilling, bit hydraulics mainly accounts for the removal of cuttings from the bottom hole by jet-erosion, and the jet from bit nozzles could hardly aid in rock-broken especially in the deep and hard formations. Therefore, the MSE model is suitable for high pressure jet drilling and soft formation drilling.

In the above MSE models, MSE's calculation containing even large sources of error due to the majority of field data is in the form of surface measurements. Especially in directional and horizontal drilling, WOB and torque of surface measurement differs greatly from bottom hole actual WOB_b and torque [12]. Therefore, few of the above MSE models can precisely model the actual downhole drilling in directional or horizontal wells. Moreover, in rotating drilling with PDM, the surface rotation is superimposed on downhole motor rotation [14]. During slide drilling, bit rotation is generated only from the PDM as drilling fluid is pumped through the drill string. However, the direct measurement of PDM rotary speed and torque in down hole has proven difficult, so few of the above MSE models can also precisely model the actual downhole drilling for rotating drilling with PDM.

2.2. Mechanical specific energy model of directional or horizontal drilling

2.2.1. Model of bottom hole WOB_b

Undersection trajectory of directional well or horizontal well can reduce drag greatly compared to a conventional tangent section due to well friction. Therefore, there is a great difference between surface measured WOB and bottom hole WOB_b at the bit. The surface measured WOB is actually the bottom hole WOB_b acting on the ground. Therefore, by analyzing the internal force of drill string produced by bottom hole WOB_b in each well section, we can get the formula between the surface measured WOB and bottom hole WOB_b.

(1) In bends section.

In 2008, Aadnoy formulated the drag model in bends and straight sections [15]. In the process of drilling, assuming the string contacts lower side, so the drag model in bends section is as follows

$$F_2 = f(\alpha_2) + (F_1 - f(\alpha_1)) \cdot e^{-\mu(\alpha_2 - \alpha_1)} \tag{5}$$

where:

$$f(\alpha) = \frac{w \cdot R}{1 + \mu^2} \left\{ \left(1 - \mu^2\right) \sin\alpha + 2\mu \cos\alpha \right\} \tag{6}$$

If $WOB_b = 0$, assuming that the force at the upper end of the bend is F_1', and the force at the lower end of the bend is F_2'. If $WOB_b > 0$, using that the force at the upper end of the bend is F_1'', and the force at the lower end of the bend is F_2'', then gives

$WOB_b = 0$:

$$F_2{}' = f(\alpha_2) + \left((F_1{}' - f(\alpha_1)) \cdot e^{-\mu(\alpha_2-\alpha_1)}\right. \tag{7}$$

$WOB_b > 0$:

$$F_2{}'' = f(\alpha_2) + \left(F_1{}'' - f(\alpha_1)\right) \cdot e^{-\mu(\alpha_2-\alpha_1)} \tag{8}$$

Eq. (7) minus Eq. (8), we get

$$F_2{}' - F_2{}'' = \left(F_1{}' - F_1{}''\right)e^{-\mu(\alpha_2-\alpha_1)} \tag{9}$$

Obviously, "$F_2{}'$-$F_2{}''$" is the internal force of drill string produced by bottom hole WOB_b at the lower end of the bend, "$F_1{}'$-$F_1{}''$" is the internal force of drill string produced by bottom hole WOB_b at the upper end of the bend. So we may express Eq. (9) as follows

$$F_{i2} = F_{i1} \cdot e^{-\mu(\alpha_2-\alpha_1)} \tag{10}$$

where:

$$\alpha_2 - \alpha_1 = \Delta\alpha = \Delta\gamma \tag{11}$$

(2) In straight sections.

In straight sections, the drag model is as follows in the process of drilling

$$F_2 = F_1 + w \cdot \Delta s \cdot (\mu \sin\alpha - \cos\alpha) \tag{12}$$

If $WOB_b = 0$, assuming that the force at the upper end is $F_1{}'$, and the force at the lower end is $F_2{}'$. If $WOB_b > 0$, using that the force at the upper end is $F_1{}''$, and the force at the lower end is $F_2{}''$, then gives.

$WOB_b = 0$:

$$F_2{}' = F_1{}' + w \cdot \Delta s \cdot (\mu \sin\alpha - \cos\alpha) \tag{13}$$

$WOB_b > 0$:

$$F_2{}'' = F_1{}'' + w \cdot \Delta s \cdot (\mu \sin\alpha - \cos\alpha) \tag{14}$$

Eq. (13) minus Eq. (14), we get

$$F_2{}' - F_2{}'' = F_1{}' - F_1{}'' \tag{15}$$

Apparently, "$F_2{}' - F_2{}''$" is the internal force of drill string produced by bottom hole WOB_b at the lower end, "$F_1{}' - F_1{}''$" is the internal force of drill string produced by bottom hole WOB_b at the upper end. So we may express Eq. (15) as follows

$$F_{i2} = F_{i1} \tag{16}$$

Therefore, in the straight sections, internal force produced by bottom hole WOB_b in each cross-section of the drill string is the same. As for straight sections, $\alpha_2 - \alpha_1 = \Delta\alpha = 0$, so Eq. (16) is the same as Eq. (10). Therefore, Eq. (10) is also suitable for straight section.

(3) Formula between WOB and WOB_b.

In the horizontal well, on the surface

$$F_i = F_{i1} = WOB, \quad \alpha_1 = 180^\circ, \gamma = 0^\circ \tag{17}$$

At the bit

$$F_i = F_{i2} = WOB_b, \quad \alpha_2 = 180^\circ + \gamma_b \tag{18}$$

and

$$\Delta\alpha = \Delta\gamma = \gamma_b \tag{19}$$

Insert Eqs. (17), (18) and (19) into Eq. (10), then we get the formula between WOB and WOB_b in horizontal well [12].

$$WOB_b = WOB \cdot e^{-\mu\gamma_b} \tag{20}$$

Figure 1 shows the relationship between weight on the bit ratio and bottom hole inclination, it indicates that there is a big difference between the surface measured WOB and bottom hole WOB_b for horizontal well drilling.

2.2.2. Model of bottom hole torque at the bit

Torque at the bit can be measured with MWD systems in the field. However, the majority of field data is in the form of surface measurements, it usually uses of surface torque to calculate MSE, which results in the value of MSE eventually is inflated by torsional friction. In horizontal drilling, the baseline trend of MSE may become several times the rock confined compressive strength (CCS). For this reason, Pessier and Fear introduced a bit-specific coefficient of sliding friction to express torque as a function of WOB, which has been widely used to compute MSE values in the absence of reliable torque measurements [7].

$$T = \int_0^{D_b/2} \int_0^{2\pi} \rho^2 \frac{4\mu_b WOB}{\pi D_b^2} d\rho d\theta = \int_0^{D_b/2} \frac{8\mu_b WOB}{D_b^2} \rho^2 d\rho = \frac{\mu_b \cdot WOB \cdot D_b}{3} \tag{21}$$

In Eq. (21), WOB is changed with WOB_b. Then we get the model of bottom hole torque at the bit [12].

$$T_b = \frac{\mu_b \cdot WOB_b \cdot D_b}{3} = \frac{\mu_b \cdot WOB \cdot e^{-\mu\gamma_b} \cdot D_b}{3} \tag{22}$$

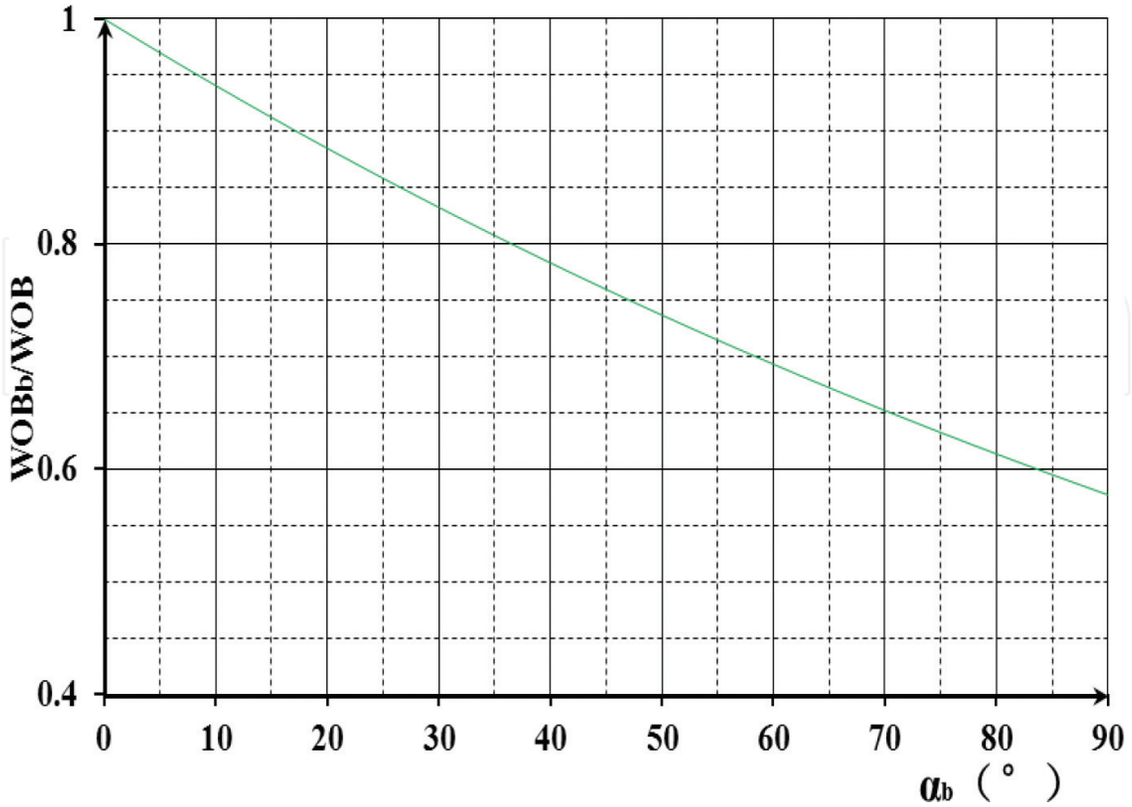


Figure 1. Relationship between weight on the bit ratio and bottom hole deviation angle (μ_b is set to 0.35) [12].

Usually the bit sliding coefficient of friction is assumed to be of an average value of 0.3 and 0.85 [16] for rollercone and PDC bits respectively.

2.2.3. Mechanical specific energy model of directional or horizontal well

WOB and torque are key variables in MSE calculation. In directional or horizontal drilling, they are greatly inflated for well friction. Eqs. (20) and (22) are the model of bottom hole WOB_b and model of bottom hole torque at the bit, which are modified by wellbore wall friction coefficient and bottom hole inclination. They can fit the bottom hole's actual working conditions. However, it has also been observed, from lab data under confined bottom hole pressure, that MSE is often substantially higher than the rock CCS, even when the bit is apparently drilling efficiently, for bit has a certain mechanical efficiency in the actual drilling process even for a new bit [5]. Finally, substitute Eqs. (20) and (22) in Teale model (Eq. (1)) and consider the mechanical efficiency (E_m) of the new bit, we can get a new model of MSE which can be shown as [12].

$$MSE = E_m \cdot WOB_b \cdot \left(\frac{1}{A_b} + \frac{13.33 \cdot \mu_b \cdot RPM}{D_b \cdot ROP}\right) \tag{23}$$

$$WOB_b = WOB \cdot e^{-\mu\gamma_b} \tag{24}$$

The bit sliding coefficient (μ_b) of friction is assumed to be of an average value of 0.3 and 0.85 for rollercone and PDC bits respectively [16]. The drill string sliding coefficient (μ) of friction is

assumed 0.25 to 0.4, usually use the value of 0.35 [17, 18]. The mechanical efficiency (E_m) of a new bit can be got by core samples' laboratory studies, or inversed by adjacent wells logging data.

2.3. Mechanical specific energy model for rotating drilling with PDM

According to the field experience, the bit's mechanical rotary energy has a much higher efficiency on rock breaking than the hydraulic energy. If the hydraulic energy of mud flow is converted into mechanical rotary power, it could improve ROP greatly. In the field, PDM has gained widespread use in the hard formation drilling to improve ROP. In rotating drilling with PDM, the power section of PDM converts hydraulic energy of mud flow into mechanical rotary power, the surface rotation is superimposed on downhole motor rotation (see **Figure 2**) [14]. Moreover, during slide drilling, bit rotation is generated only from the PDM as drilling fluid is pumped through the drill string. Due to the direct measurement of PDM rotary speed and torque in down hole has proven difficult, so currently there are few effective MSE models to precisely model the actual downhole drilling for rotating drilling with PDM.

2.3.1. PDM performance

In PDM, the power section converts hydraulic energy of mud flow into mechanical rotary power. The output parameters of its mechanical horsepower are rotor torque and rotary speed, whereas differential pressure and mud flow rate are its operational parameters. However, the direct measurement of PDM rotary speed and torque in down hole has proven difficult. The key design parameter that relates PDM output parameters to its operational parameters is PDM unit displacement. It is defined as the mud volume required to revolve a PDM rotor shaft one revolution and can be found on PDM performance data sheets. Then the ideal PDM output torque and rotary speed can be defined by [19].

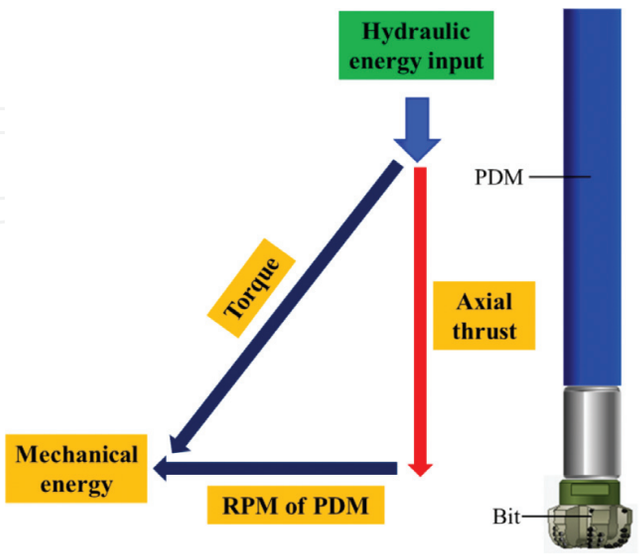


Figure 2. PDM converts hydraulic energy of mud flow into mechanical rotary power [14].

$$T_{ideal} = 3.066 \cdot \Delta P_m \cdot q \tag{25}$$

$$RPM_{ideal} = \frac{Q}{q} \tag{26}$$

However, in actual drilling process, leakage and torque losses play important roles in the performance of a PDM. The actual rotary speed of the PDM is decreased by the slip flow through the seal line, and the actual torque is also decreased by the resisting torque due to mechanical friction, elastomeric friction and viscous shearing of drilling fluid. The actual PDM output torque and rotary speed can be estimated by

$$T_m = T_{ideal} - \Delta T \tag{27}$$

$$RPM_m = \frac{Q - Q_{slip}}{q} \tag{28}$$

Torque losses is given by [20].

$$\Delta T = \frac{\pi^2 i^4}{2(1-i)(2-i)^3} \frac{RPM_m}{\delta} D_h^3 L_s \mu + C_f \frac{\pi(1-i^2)}{4(2-i)^2} D_h^2 p_h \Delta P_m + \frac{2F_n y}{3\pi} \tag{29}$$

Slip flow is estimate as

$$Q_{slip} = \frac{\pi \delta^3 D_h n_s \Gamma_i \tan\alpha}{12\mu L_s L_m} \left(\frac{i}{1-i}\right) \Delta P_m \tag{30}$$

In Eqs. (29) and (30), many parameters are functions of motor geometry, property and even drilling conditions, some of them are difficult to be determined. Therefore, the prediction of T_m and RPM_m has proven difficult. However, in PDM the mechanical power is converted by hydraulic horsepower, and it depends on the converting efficiency of the PDM. Then the mechanical power can be predicted based on its input hydraulic power. The mechanical horsepower provided by PDM can be estimated by [21].

$$MHP = \frac{T_m}{550} \left(\frac{2\pi}{60}\right) \cdot RPM_m \tag{31}$$

The hydraulic horsepower can be given as

$$HHP = \frac{Q \cdot \Delta P_m}{1714} \tag{32}$$

Their relationship can be written as

$$MHP = \eta \cdot HHP \tag{33}$$

In Eqs. (32) and (33), the operating differential pressure drop across the motor, at a constant flow rate, can be measured by comparing off-bottom (zero torque) and on-bottom surface

standpipe pressures. Flow rate can also be easily obtained on the surface. The efficiency of a particular type of motor can be estimated based on data measured on test stands [22].

2.3.2. A MSE model for rotating drilling with PDM

In rotary-drilling with PDM (see **Figure 3**), the mechanical work required to remove a unit volume of rock comes from the WOB, torque at bit provided by surface rotation and torque at bit provided by PDM rotation. The total mechanical work done by the bit in 1 h can be estimated as

$$W_{\mathrm{t}} = WOB_b \cdot ROP + 60 \cdot 2\pi \cdot RPM_s \cdot T_s + 60 \cdot 2\pi \cdot RPM_m \cdot T_m \tag{34}$$

In the above model, RPM_s is bit rotary speed provided by surface rotation; T_s is torque at bit provided by surface rotation; RPM_m is PDM output rotary speed; T_m is PDM output torque. As PDM is near above bit, bit rotary speed and torque provided by PDM can be nearly considered as PDM's output rotary speed and torque.

Please note that every bit has a mechanical efficiency for drilling when it is produced. The mechanical efficiency is mainly related to the bit's cutting structure and exists all along the drilling process [10, 11]. Given the mechanical efficiency of the new bit, the mechanical work required to break the rock drilled in 1 h can be nearly expressed as

$$W_V = W_t \cdot E_m \tag{35}$$

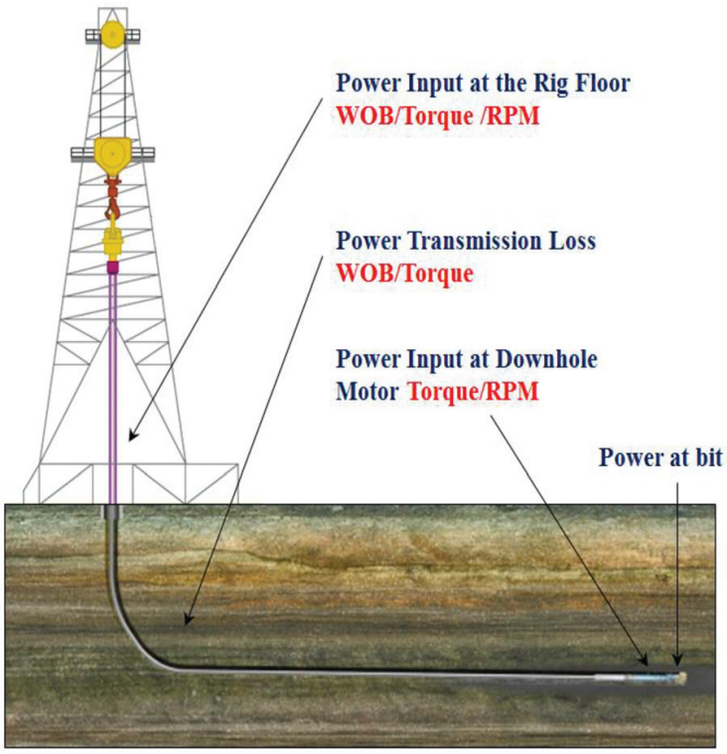


Figure 3. Rotating drilling system with PDM [14].

The volume of rock drilled in 1 h is

$$V = A_b \cdot ROP \tag{36}$$

MSE has been defined as the mechanical work done to excavate a unit volume of rock. By combining Eqs. (34), (35) and (36), then the MSE for rotating drilling with PDM can be expressed by

$$MSE = \frac{W_V}{V} = E_m \cdot \frac{WOB_b \cdot ROP + 60 \cdot 2\pi \cdot RPM_s \cdot T_s + 60 \cdot 2\pi \cdot RPM_m \cdot T_m}{A_b \cdot ROP} \tag{37}$$

However, the mechanical energy provided by the surface has a great transmission loss in horizontal and directional drilling. Chen et al. formulated a relationship between bottom hole WOB and the surface measured WOB and presented a method to calculate torque of bit in directional and horizontal drilling [12].

$$\begin{aligned} WOB_b &= WOB \cdot e^{-\mu_s \gamma_b} \\ \mu_b &= 36 \frac{T_s}{D_b \cdot WOB \cdot e^{-\mu_s \gamma_b}} \end{aligned} \tag{38}$$

Then the mechanical specific energy provided by the surface can be estimated as

$$\begin{aligned} &E_m \cdot \frac{WOB_b \cdot ROP + 60 \cdot 2\pi \cdot RPM_s \cdot T_s}{A_b \cdot ROP} \\ &= E_m \cdot WOB \cdot e^{-\mu_s \gamma_b} \left(\frac{1}{A_b} + \frac{13.33 \cdot \mu_b \cdot RPM_s}{D_b \cdot ROP} \right) \end{aligned} \tag{39}$$

According to Eqs. (31), (32) and (33), the mechanical specific energy provided by the down hole motor can also be estimated as

$$E_m \cdot \frac{60 \cdot 2\pi \cdot RPM_m \cdot T_m}{A_b \cdot ROP} = E_m \cdot \frac{1155.2 \cdot \eta \Delta P_m Q}{A_b \cdot ROP} \tag{40}$$

Finally, substitute Eqs. (39) and (40) into Eq.(37), we can get a new MSE model for rotating drilling with PDM [14].

$$MSE = E_m \cdot \left(WOB \cdot e^{-\mu_s \gamma_b} \left(\frac{1}{A_b} + \frac{13.33 \mu_b \cdot RPM_s}{D_b \cdot ROP} \right) + \frac{1155.2 \cdot \eta \Delta P_m Q}{A_b \cdot ROP} \right) \tag{41}$$

For slide drilling, bit rotation is generated only from the PDM as drilling fluid is pumped through the drill string. The MSE can be estimated by [14].

$$MSE = E_m \cdot \left(WOB \cdot e^{-\mu_s \gamma_b} \cdot \frac{1}{A_b} + \frac{1155.2 \cdot \eta \Delta P_m Q}{A_b \cdot ROP} \right) \tag{42}$$

Note that ΔP_{m} is the pressure drop across the PDM, and η is the efficiency of PDM but not the bit. $\mathrm{RPM_s}$ is drill pipe rotary speed.

3. Drilling performance prediction and optimization based on mechanical specific energy technologies

3.1. Confined compressive strength

Teale's laboratory experiment showed that MSE was numerically close to the unconfined compressive strength (UCS) of the formation at maximum drilling efficiency [6]. However, the tests were conducted at atmospheric conditions. In the real drilling process, MSE is numerically close to the CCS of the formation at maximum drilling efficiency. In other words, when drilling achieves a maximum drilling efficiency, the minimum MSE is reached and is roughly equal to the CCS of the rock drilled [14].

$$MSE(\min) = CCS \tag{43}$$

Therefore, MSE can be used to detect the peak drilling efficiency by surveilling MSE to see if the MSE(min) is roughly equal to the CCS of the rock drilled.

The widely practiced and accepted method for calculating CCS of rock is as follows [18].

$$CCS = UCS + D_p + 2D_p \cdot \frac{\sin\phi}{1 - \sin\phi} \tag{44}$$

In bottom-hole drilling conditions, for permeable rock, the bottom hole confining pressure can be expressed as

$$D_p = ECD_p - P_p \tag{45}$$

3.2. Drilling performance prediction and optimization for directional or horizontal drilling

3.2.1. Rate of penetration model based on mechanical specific energy

The rock strength at the rock-bit interface is best defined by CCS. Given the MSE model of directional or horizontal drilling takes the mechanical efficiency (E_m) of the new bit into account, so we can assume that MSE is equal to the CCS of the formation. Substituting MSE in terms of CCS, then ROP can be predicted as follows [12].

$$ROP = \frac{13.33 \cdot \mu_b \cdot RPM}{D_b\left(\frac{CCS}{E_m \cdot WOB \cdot e^{-\mu\gamma_b}} - \frac{1}{A_b}\right)} \tag{46}$$

The above ROP model is relatively simple. By using this model we can quickly predict the ROP with reasonable accuracy for all of the bit types, according to the formation properties and the drilling environment. One limitation of the ROP model is that it does not recognize the founder point of any given bit, which means it can predict a higher ROP than is achievable as WOB and RPM increase beyond the bit's optimum combination [23].

3.2.2. Drilling performance prediction and optimization method

MSE is the amount of energy required to destroy a unit volume of rock and it provides a means of evaluating and optimizing drilling performance. By comparing MSE to the predicted CCS, as well as by comparing actual ROP to the predicted ROP, drilling performance and bit condition can be evaluated. The drilling performance can be evaluated and predicted by Eqs. (44) and (46). When MSE is equal to the predicted CCS, or actual ROP is equal to the predicted ROP, it indicates that drilling performs well and the bit is operating at its peak efficiency.

Drilling performance optimization based on MSE technologies means real-time analyzing of MSE and adjusting drilling parameters accordingly to minimize drilling problems and maximize ROP. When a bit is operating at its peak efficiency, the ratio of energy to rock volume will remain relatively constant, and MSE is nearly equal to the CCS of the formation. This relationship is used operationally by observing whether the minimum MSE is equal to the CCS of the formation while adjusting drilling parameters such as WOB or RPM to maximize ROP. If the minimum MSE remains equal to the CCS of the formation while increasing WOB, the bit is assumed to be still efficient. If MSE increases significantly and is much higher than the CCS of the formation, the bit has foundered and drilling problems may occur, such as vibrations, bit balling, bottom hole balling and dull bits. The driller then determines the most likely cause of founder and drilling problems, and adjusts parameters accordingly. Adjustments continue to be made until the MSE value is minimized equally to CCS of the formation.

Based on the relations between MSE, drilling parameters and ROP, an appropriate predicting and optimizing method can be proposed by analyzing bottom-hole conditions of drilling and determining the reasonability of drilling parameters. **Figure 4** is the flow chart of the drilling performance prediction and optimization method [12].

As shown in **Figure 4**, when MSE(min) = CCS, and ROP/WOB = constant >0, it is in the region B as **Figure 5** [12] indicate. MSE is low and nearly equal to CCS. The slope of the line is relatively constant for a given formation, bit and rotary speed. The drilling efficiency remains at its peak efficiency. In this region, the bit is not constrained by a unique inefficiency, it simply needs more energy. Just by increasing WOB or RPM, the ROP will increase greatly and eventually approach the founder point. When ROP/WOB≠constant > 0, it is close to the highest ROP that can be achieved with the current system and reached the region C. But if ROP further increases, then bit balling and bottom hole balling will occur. Therefore drilling parameters should be better set in the area near to the founder point to ensure that drilling performs efficiently and safely. Real-time MSE surveillance can be used to find the founder point. If MSE remains constant, the bit is efficient, if the MSE rises, the system is foundering.

When MSE(min) > CCS, it is in the region C, MSE is high and even several time of CCS. As ROP increases, down hole cuttings accumulate, which leads to bit balling, bottom hole balling, and constrains the energy from bit transfer to the rock, as a result ROP drops. If WOB further increases, vibrations will occur and ROP will decrease greatly. In this region, in order to extend

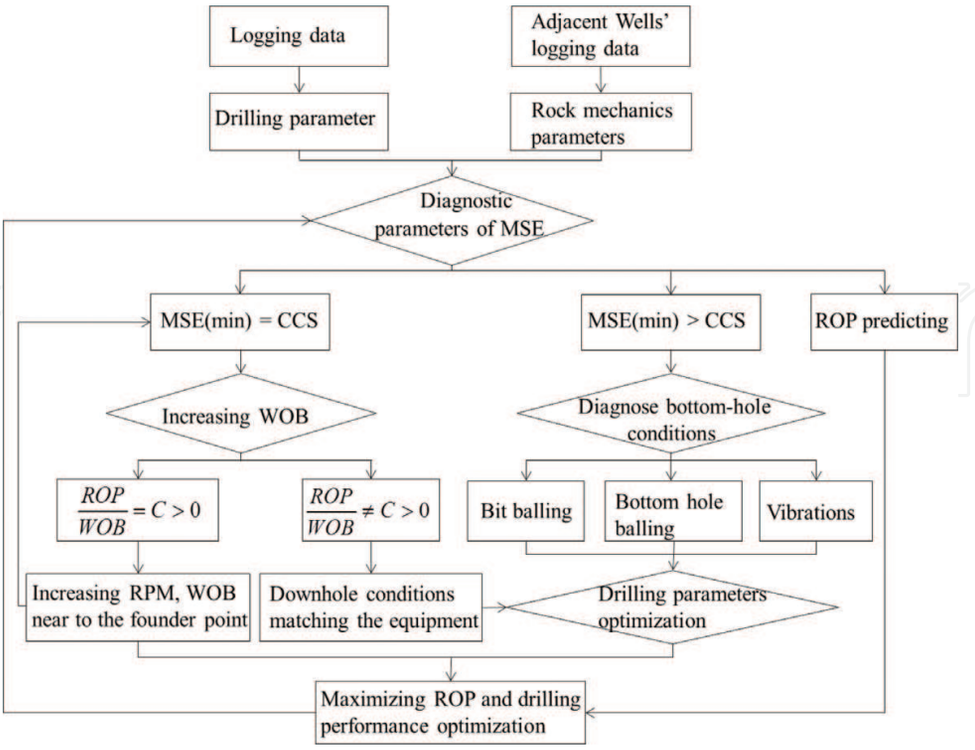


Figure 4. Flow chart of drilling performance prediction and optimization [12].

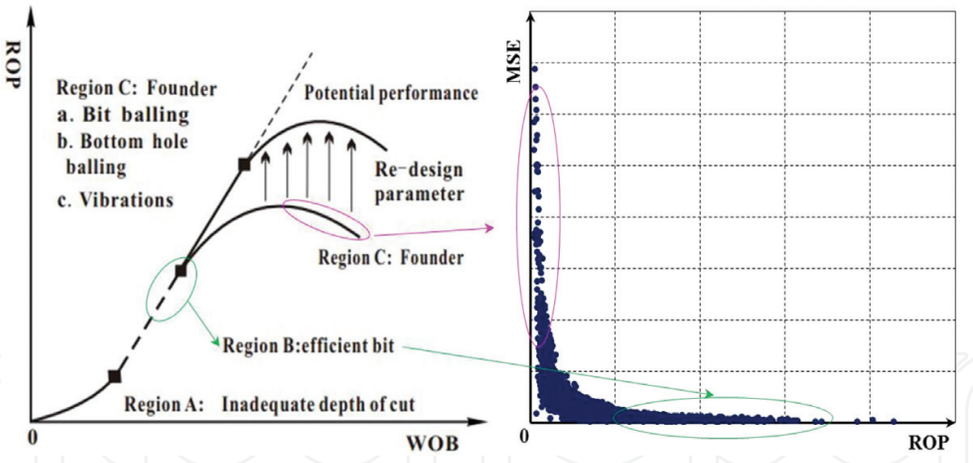


Figure 5. Relationship between the traditional ROP vs. WOB plot and the new MSE vs. ROP plot [12].

the range of balling period and maximize ROP, nozzles and flow rates can be modified to achieve the highest hydraulic horsepower per square inch (HSI) possible with the available rig equipment. If reaching the rated power of the equipment, WOB should reduce, and drilling parameters should be set in the intersect area between region B and region C.

3.3. Drilling parameters optimization for rotating drilling with PDM

Real-time optimization of drilling parameters during drilling operations aims to optimize WOB, RPM for obtaining maximum ROP [24, 25]. The process is not only formation specific

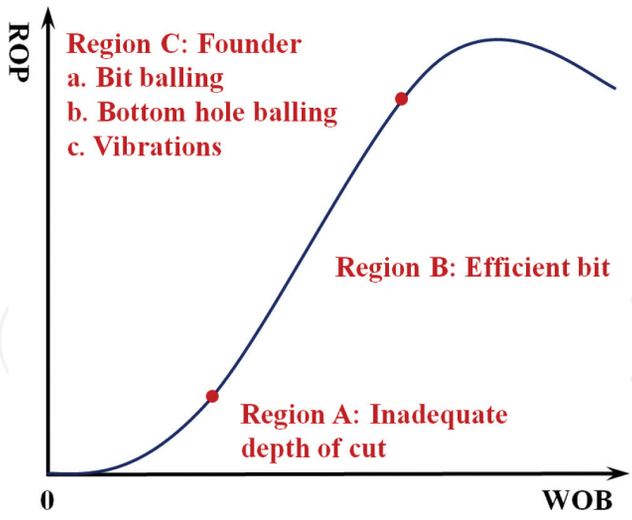


Figure 6. Relationship between the traditional ROP versus WOB plot [14].

but also drilling system specific. **Figure 6** shows a classic drill-off curve [5]. The point at which the ROP stops responding linearly with increasing WOB is referred to as the founder point where the ROP is maximized. The corresponding WOB at this point is taken to be the optimum WOB. **Figure 7** shows field data from three drill-off tests with an insert bit [5, 14]. It indicates that the bit is prone to founder with high RPM, and the optimum WOB decreases obviously with the increase of RPM of bit. Moreover, the founder point changes greatly with the change of RPM of bit. In rotating drilling with PDM, the surface rotation is superimposed on PDM rotation, the RPM of bit is high and could be changed greatly. It not only makes the bit be easy to reach the founder point even at low WOB, but also makes the founder point be difficult to be identified. MSE surveillance provides an objective assessment of the drilling efficiency and an

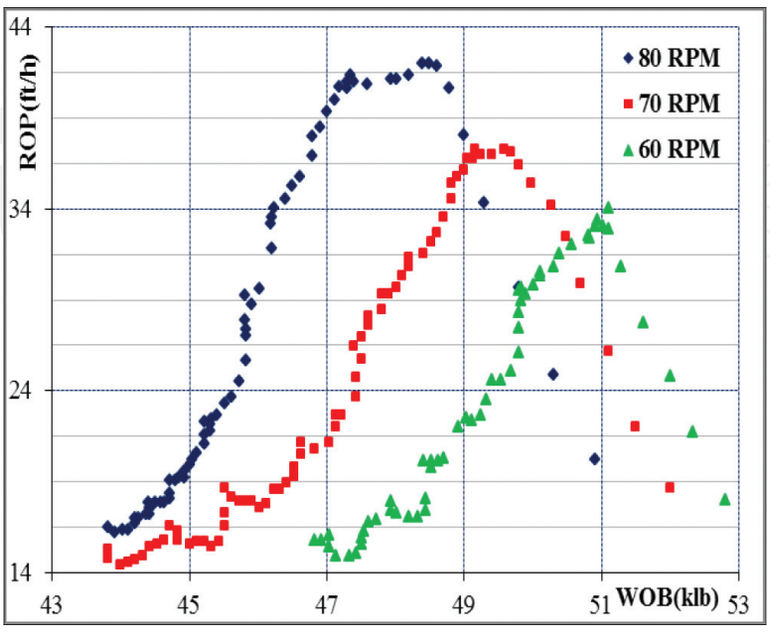


Figure 7. Field data from three drill-off tests [5].

objective tool to identify the founder point. Therefore, real-time optimization of drilling parameters for rotating drilling with PDM can be performed by identifying the founder point of the bit in specific formation drilling based on MSE surveillance.

As aforementioned, MSE is the amount of energy required to destroy a unit volume of rock. When a bit is operating at its peak efficiency, the ratio of energy to rock volume will remain relatively constant. The minimum MSE is reached and it correlates with the CCS of the formation. This relationship is used operationally by observing whether the MSE(min) is roughly equal to the CCS of the formation while adjusting drilling parameters such as WOB or RPM to maximize ROP. If the MSE(min) remains roughly equal to the CCS of the formation while increasing WOB, the bit is assumed to be still at its peak efficient. If the MSE(min) increases significantly and is much higher than the CCS of the formation, the bit has foundered. The causes of founder are bit balling, bottom hole balling and vibrations. If the causes of founder are not addressed when they occur, overall drilling performance will suffer and tools will be damaged.

Bit balling and bottom hole balling are terms used to describe build-up of material on the bit and bottom hole that inhibits transfer of a portion of the WOB to the cutting structure. They usually occur in soft formations, and can be relieved by increasing flow rates and reducing WOB. When drilling in hard formation with a PDM, bit balling and bottom hole balling are unlikely to occur, while vibrations are very common. Down hole vibrations include three modes: whirl (lateral), stick-slip (torsional) and bit bounce (axial). They amplify loads downhole, resulting in a host of bit and tool failures that not only increase the number of trips required, but also the costs of tool repair and replacement. Actually these vibrations in rotating drilling with PDM could be effectively eliminated by adjusting WOB or RPM on the surface.

Whirl can be effectively eliminated by reducing RPM while increasing WOB. Stick-slip can be minimized by reducing WOB and increasing RPM. As for bit bounce, if the bouncing is initiated when running high WOB and low RPM, the solution is to increase RPM and reduce WOB. Conversely, if the problem begins with higher RPM and lower WOB, the answer is to reduce RPM and increase WOB. It may also even be necessary to stop surface rotation and simply drill in slide mode (bit rotation is generated only from the PDM) through the problematic formation [26].

Assume the bottom hole is effectively cleaned, then based on the above analysis, a drilling parameters optimization method for rotating drilling with PDM can be proposed to maximize ROP and allow operators to drill longer and avoid unnecessary trips. **Figure 8** is the flow chart of the drilling parameters optimization method for rotating drilling with PDM [14], and it is based on real-time MSE surveillance to find the founder point of the bit [12]. When MSE (min) = CCS, the bit performs in the region B as shown in **Figure 6** and the drilling efficiency remains at peak efficiency. In this region, the bit is not constrained by a unique inefficiency, it simply needs more energy. Given a RPM, just by increasing WOB, the ROP will increase greatly and eventually approach the founder point.

When MSE(min) > CCS, and MSE(min) is even several time of CCS, the bit is floundering and drilling problems may occur. Adjustments of WOB and RPM need to be made until the MSE (min) value is minimized and roughly equal to the CCS of the formation. The process of

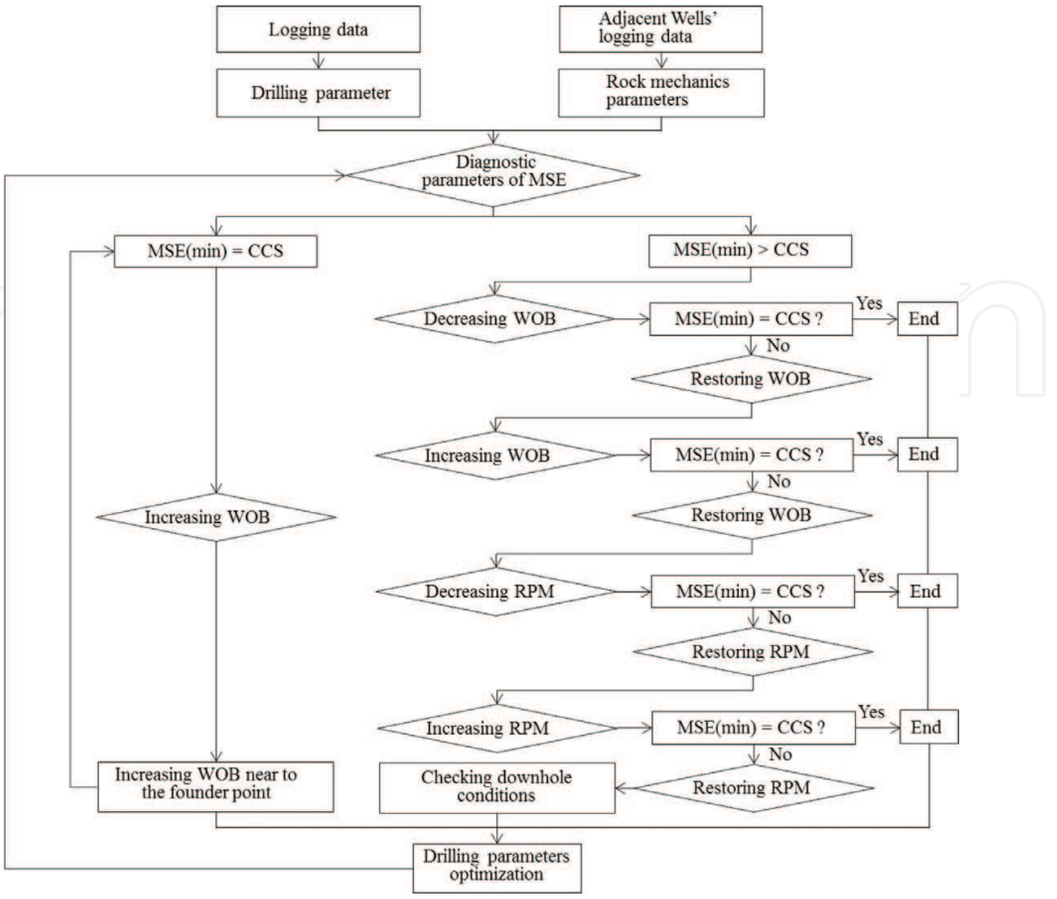


Figure 8. Flow chart of drilling parameters optimization for rotating drilling with PDM [14].

adjustment is shown in **Figure 8**. As drilling with PDM provides much higher RPM at the bit than the conventional rotating drilling could achieve, the bit is easy to reach the founder point even with low WOB. Further increasing WOB or RPM is more likely to decrease ROP and worsen the drilling problems. Moreover, high WOB that will generate excessive torque for the PDM may make PDM stalled, and RPM may also cause excessive vibration of the drill pipe. Therefore, the adjustment for rotating drilling with PDM is to reduce WOB first and then gradually increase WOB, and do the same manipulation for RPM until MSE(min) = CCS. The adjustment should not be in a very wide range. If MSE still much higher than the CCS of the formation after the adjustment of WOB and RPM, down hole conditions should be checked to see if the bit and PDM were damaged.

4. Field case

4.1. Field case no.1: verification of MSE model and drilling performance prediction of directional or horizontal drilling

In order to verify the accuracy of the MSE model of directional or horizontal drilling, several other key models of MSE (such as Teale model [6], Pessier model [7], Dupriest model [5]) are

carried out and compared against field data. Initially, MSE is calculated respectively by these MSE models using surface measured data and plotted vs. depth. The results are compared with the rock CCS to verify the accuracy of the MSE model of directional or horizontal drilling. Then, the actual ROP and the predicted ROP which is calculated with Eq. (46) are both plotted vs. depth to verify the accuracy of the ROP prediction model, and the drilling parameters WOB, RPM, and MSE are also plotted vs. depth to explain the observed pattern. Furthermore, actual ROP and the predicted ROP of each bit are also plotted.

This well's trajectory is designed with a kick-off point (KOP) at 2925 m with a build rate of 5°/30 m dogleg severity (DLS) until reaching 90° at 3465 m, and then steered a horizontal section to 4043 m measured depth. The log data of vertical section and horizontal section are used to calculate MSE respectively by Teale model, Pessier model, Dupriest model and the MSE model of directional or horizontal drilling. CCS is determined by Eq. (44) to verify the accuracy of these models. The comparison of MSE calculated results and CCS are showed on **Figures 9** and **10** respectively in vertical section and horizontal section. It shows that the calculation errors of Teale model, Pessier model, Dupriest mode are apparently inflated in horizontal section. The MSE estimated with the MSE model of directional or horizontal drilling has the best correlation with CCS, and the order of models from good to poor in accurately predicting correlation effect is the MSE model of directional or horizontal drilling, Pessier model, Dupriest model and Teale model. In vertical section, the correlation effect of MSE model of directional or horizontal drilling, Pessier model, Dupriest model is relatively close, but far better than Teale model. In horizontal section, MSE values calculated with Teale model is more than 10 times of CCS, and MSE values calculated with Pessier model and Dupriest model are several times of CCS. As for the MSE model of directional or horizontal drilling, its MSE values are close to CCS. The correlation effect of the MSE model of directional or horizontal drilling in horizontal section is close to that of in vertical section. So the correlation effect of the MSE model of directional or horizontal drilling is apparently better than Pessier model, Dupriest model and Teale model in both vertical section and horizontal section.

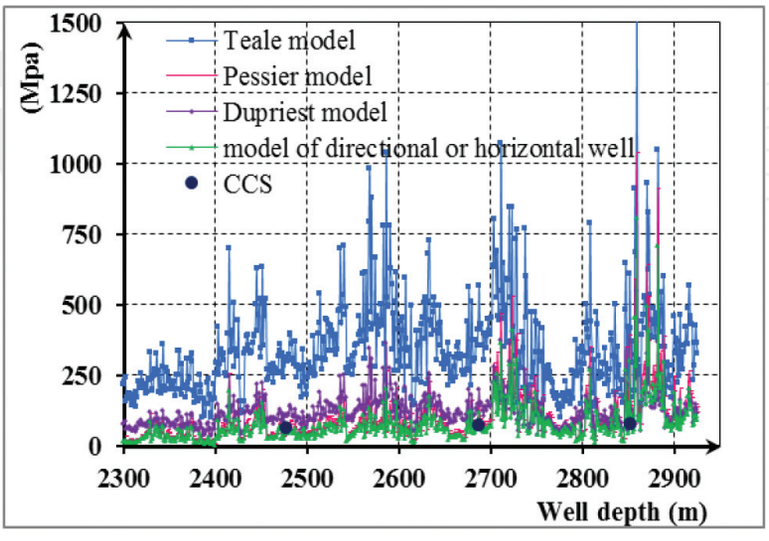


Figure 9. Comparison of MSE calculated results and testing CCS in vertical section.

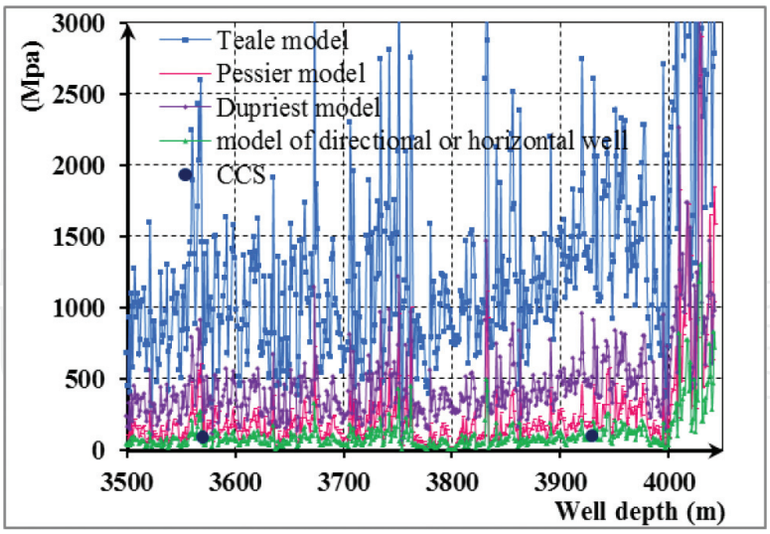


Figure 10. Comparison of MSE calculated results and testing CCS in horizontal section.

Figure 11 plots the predicted ROP and the actual ROP vs. depth, and the drilling parameters WOB, RPM, and MSE are also included on **Figure 11**. The predicted ROP is calculated with Eq. (46). As indicated in **Figure 11**, the predicted ROP matches well with the actual ROP, which reveals that the ROP predict model's prediction accuracy is high, and can fully meet the needs of the field. Therefore, the MSE model of directional or horizontal drilling can be quantitatively applied. **Figure 12** plots ROP prediction accuracy of each bit. A, B, and C bit's ROP prediction accuracy respectively are 84.8% (A), 91.2% (B), 76.8% (C). In the section of 2700–2750, 2830–2890 and 3167–3215 m, the predicted ROP is higher than the actual ROP. The drilling parameters WOB, RPM, and MSE plotted vs. depth are used to explain the observed pattern in **Figure 11**.

In 2700–2750 m, MSE value increases and actual ROP reduces greatly, and the predicted ROP is higher than the actual ROP. After the WOB increases from 30 to 52 kN from 2730 to 2766 m, MSE value reduces to the baseline trend and the actual ROP increases. In this section, as the hydraulics and bit rotating speed don't change, so it can't be bit balling and bottom hole inadequate cleaning. Therefore, it is likely that whirl leads energy cannot effectively passed to the bit, as a result actual ROP decreases. And in fact, whirl is also observed in this section. In 2830–2890 m and 3167–3215 m, MSE value increases slowly and actual ROP reduces greatly, trip-out and discovery that bit was badly damaged. Change a new bit and drill with the same drill parameter, MSE value decreases and actual ROP increases.

4.2. Field case no.2: drilling parameters optimization for rotating drilling with PDM

To verify the new mechanical specific energy model, drilling data of a 2621-ft section of a vertical well have been used to calculate the profiles of CCS and MSE with depth. The drilling data, including WOB, surface RPM, ROP, mud flow rate and on-bottom PDM differential pressure, were recorded for every 1-ft step from 4072 to 6693 ft. The lithology is limestone and the section was drilled with 22 in bits and a 9:10 lobe ratio PDM. The efficiency of PDM is

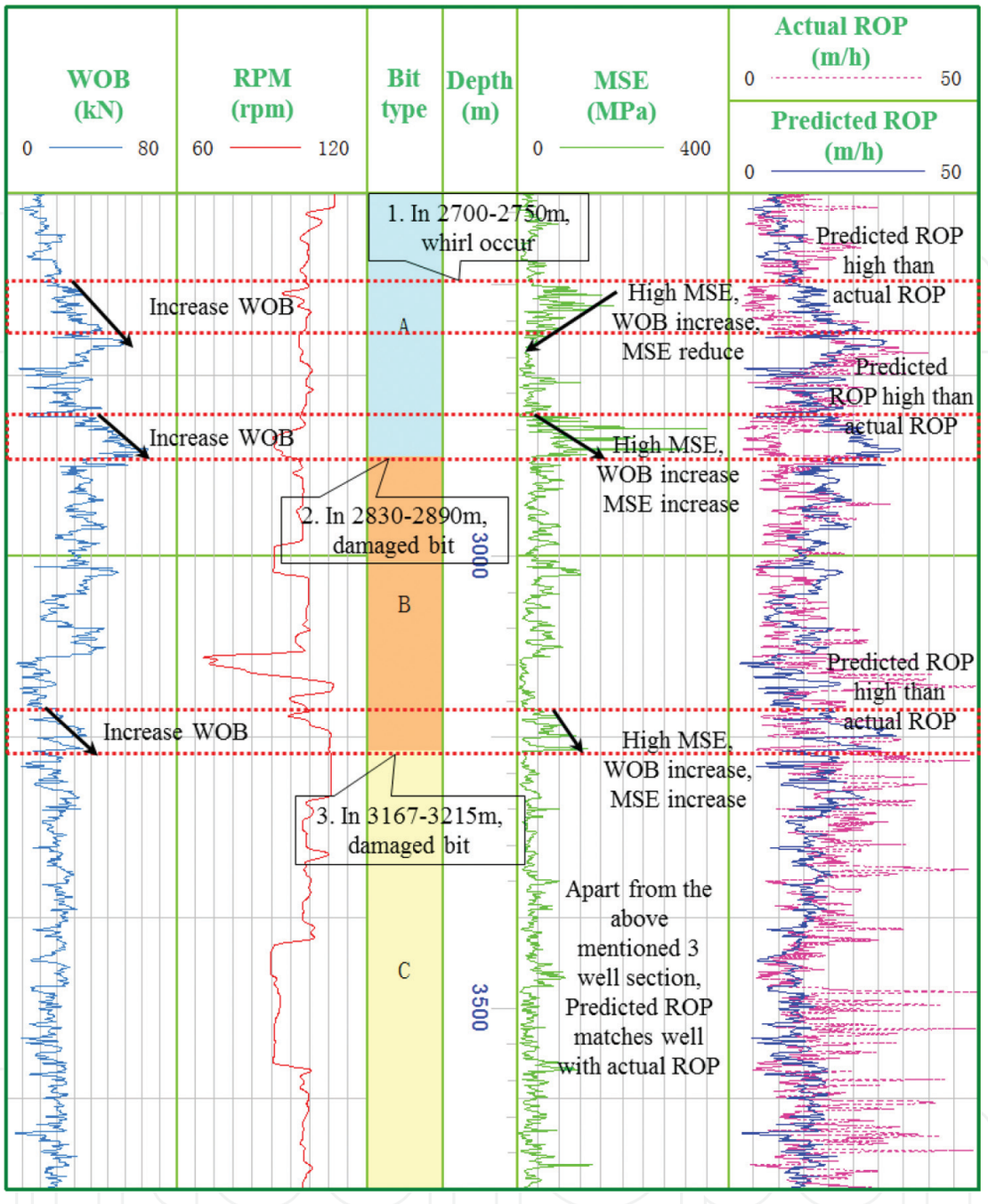


Figure 11. ROP predicted result and bottom-hole condition analysis.

70%. MSE is estimated by the new MSE model for rotating drilling with PDM (Eq. (41)). CCS is calculated by Eq. (44) using the field's log data. The comparison of the calculated MSE against CCS is shown in **Figures 13** and **14**. **Figure 13** shows the MSE(min) is roughly equal to the CCS of the formation almost along all the well depth apart from the well sections: 5502–5606 ft, 5948–6045 ft, 6564–6693 ft. In the sections of 5502–5606 ft and 5948–6045 ft, the applied WOB is very high and more than 46 kbl. Severe vibrations were observed in these two sections. In the section of 6564–6693 ft, relatively low WOB is applied and around 8–20 kbl. While trip-out, it is

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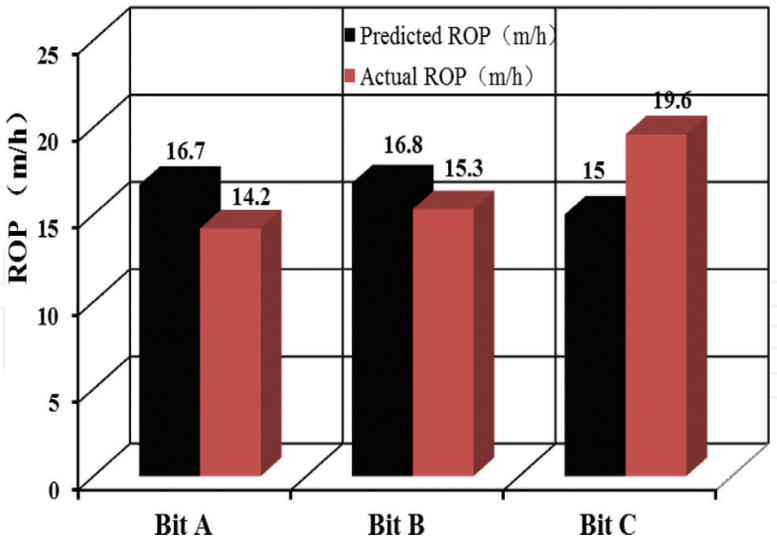


Figure 12. ROP predicted results of different bits type.

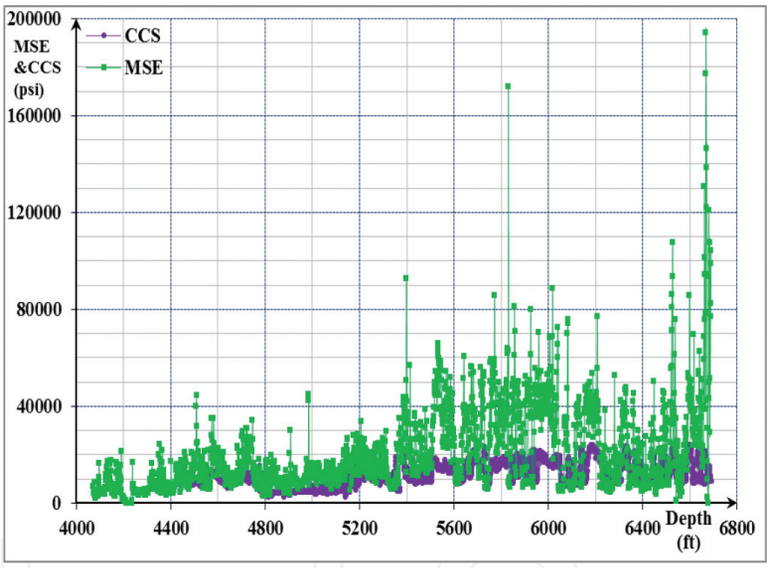


Figure 13. MSE and CCS vs depth.

found that the bit was badly damaged. **Figure 14** reveals that the MSE values are minimized and have good correlation with the CCS when the ROP is high, while with low ROP the MSE values are obviously higher than the CCS of the formation. Therefore, when drilling with a high efficiency and free of drilling complications, the MSE(min) estimated by the MSE Model for rotating drilling with PDM is roughly equal to the CCS of the formation along all the well depth. This indicates that the MSE Model for rotating drilling with PDM estimates MSE values with a reasonable approximation and can meet the needs of field applications.

In order to demonstrate the applicability of the proposed drilling parameters optimization method, drilling operation of a 2855-ft interval of an anhydrite and dolostone formation with a 9.5 in PDM and 16 in PDC bit is analyzed to determine the optimum WOB value in the same

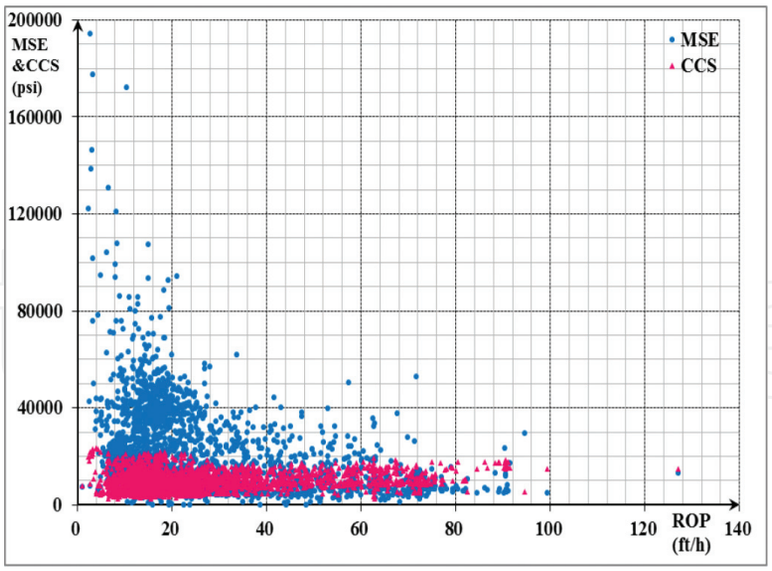


Figure 14. MSE and CCS vs ROP002E.

vertical well from 7651 to 10,499 ft. The PDM is a high RPM motor with a 5:6 lobe configuration which provides moderate torque values. PDM unit displacement is 6.67 gal/rev, and the PDM output rotary speed is estimated by Eq. (26).

Figure 15 plots the drilling parameters versus depth to illustrate the sensitivity of ROP and MSE of this operation to WOB and RPM. MSE vs. ROP and the average ROP of various well

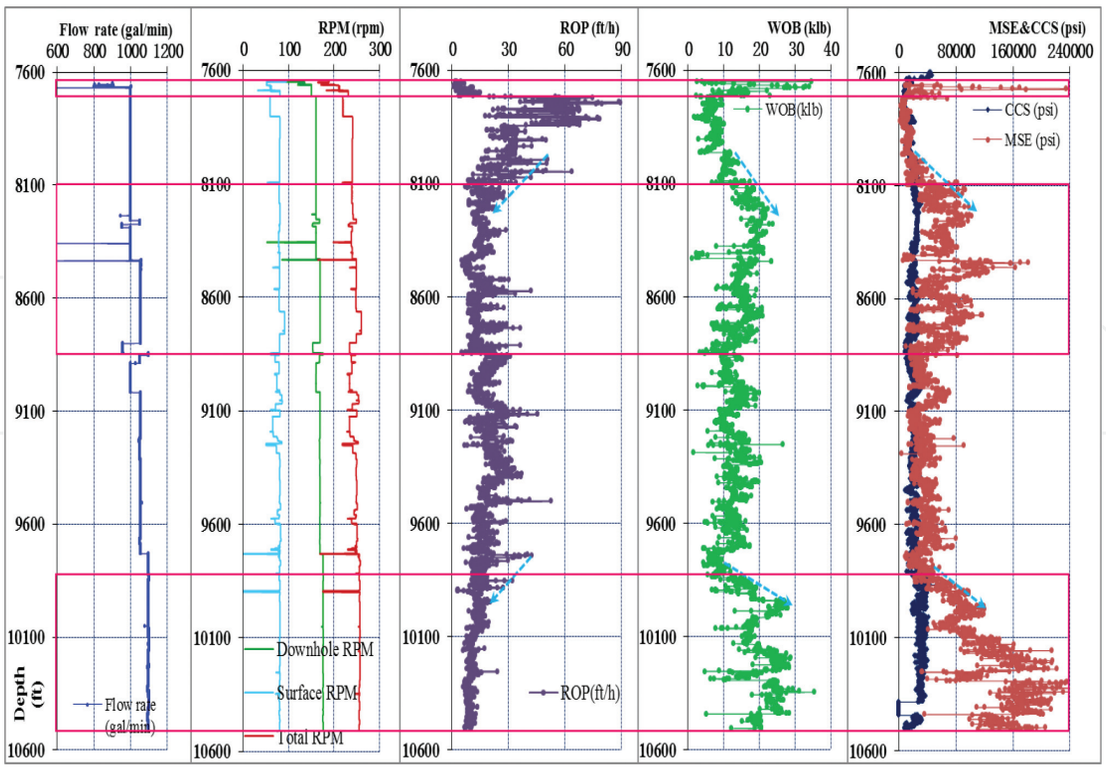


Figure 15. Drilling parameters optimization.

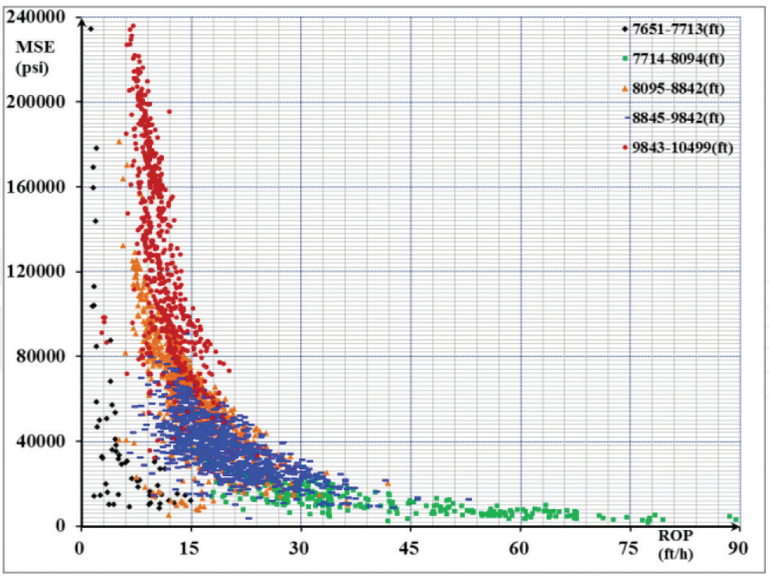


Figure 16. MSE vs ROP.

sections are respectively shown in **Figures 16** and **17**. From 7651 to 7713 ft, the applied WOB is as high as 34.7.4 kbl, the value of MSE is apparently greater than CCS (MSE(min) > CCS). This indicates that the bit is foundered and the average ROP is 5.9 ft/h. From 7714 to 8094 ft, WOB is adjusted to around 6.6–11 kbl and RPM almost remains at 240, then MSE(min) = CCS and the average ROP increases to 38.1 ft/h. It drills with high efficiency. At around 8084 ft, when WOB further increases from 8.8 to 11 kbl, the MSE value increases obviously and MSE(min) > CCS. From 8095 to 8842 ft, WOB increases to around 17.6 kbl. However, the MSE(min) mounts up to several times of CCS, and the average ROP decreases to 15.1 ft/h. At 8435 ft, when the flow rate increases to 1056.0 gal/min from 1001.6 gal/min and RPM increases to 249 from 240, the MSE

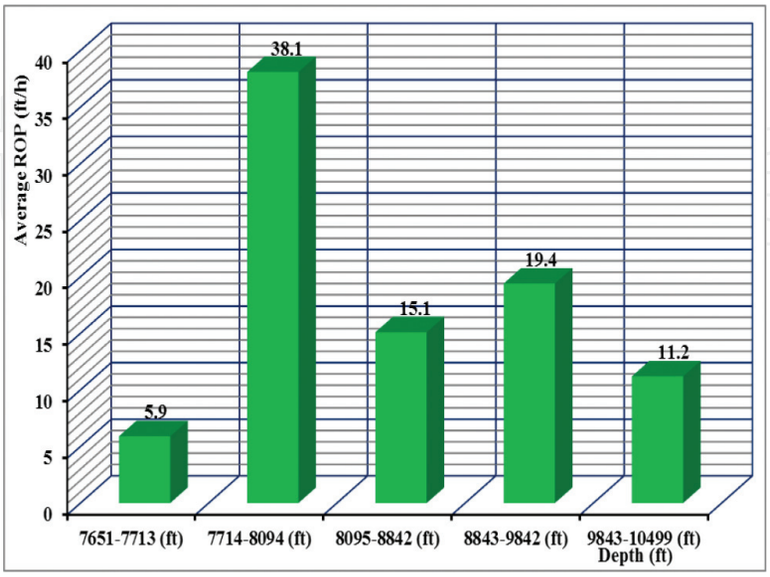


Figure 17. The average ROP.

value further inflates. Therefore, when RPM is around 240, the drilling system's optimum WOB is 8.8–11 kbl. At around 8843 ft, WOB is adjust to 8.8–11 kbl, the MSE value is minimized and close to the CCS of the formation. From 8843 to 9842 ft, WOB remains around 8.8–11 kbl, it drills with a relatively high efficiency and the average ROP is 19.4 ft/h. At 9731 ft, the flow rate increased to 1097.6 gal/min from 1056.0 gal/min and RPM increased to 258 from 249. The MSE value is minimized and MSE (min) = CCS while WOB reduced to 7.3–9.5 kbl. At 9888 ft, when WOB increases from 7.3 to 9.5 kbl, the MSE value rockets and MSE(min) > CCS. From 9843 to 10,499 m, WOB increases to more than 26.5 kbl, the MSE value is more than ten times of CCS and the average ROP is 11.2 ft/h. This indicates that when RPM is around 258, the drilling system's optimum WOB is 7.3–9.5 kbl.

Based on the above drilling parameters optimization analysis, it is also found that ROP is sensitive to high WOB values for rotating drilling with PDM, and increasing WOB does not always increase ROP but is more likely to decrease ROP. Moreover, the optimum WOB always changes with RPM for rotating drilling with PDM. The proposed method for optimizing drilling parameters can be used to real time estimate optimum WOB values with different RPM to drill a specific formation interval. It can be effectively and easily used, and is worthy to be applied and promoted.

5. Summary and conclusions

In this chapter, MSE models respectively for directional or horizontal drilling and rotating drilling with PDM are established, meanwhile methods for drilling performance prediction and optimization based on MSE technologies are presented. The following remarks provide a summary with conclusions on the basis of case studies.

1. A formula between bottom hole WOB_b and the surface measured WOB is developed, and the bottom hole WOB_b has been introduced to calculate torque of bit of directional or horizontal wells.
2. The MSE models respectively for directional or horizontal drilling and rotating drilling with PDM estimate MSE values with a reasonable approximation in the absence of reliable torque measurements, they can be widely used in the drilling industry.
3. ROP is sensitive to high WOB values for rotating drilling with PDM. The optimum WOB is low for rotating drilling with PDM compared with the conventional drilling without PDM, increasing WOB does not always increase ROP but is more likely to decrease ROP.
4. The method for optimizing drilling parameters can real time estimate optimum WOB values with different RPM to drill a specific formation interval with PDM. It could be effectively used to maximize ROP and allow operators to drill longer and avoid unnecessary trips in rotating drilling with PDM.
5. Drilling performance prediction and optimization methods based on MSE technologies is worthy to be applied and promoted with highly diagnostic accuracy, effective optimizing and simple operation.

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Nomenclature

A_b	bit area (in^2)
CCS	confined compressive strength (psi)
C_f	coefficient of dry friction and is assumed to be constant for all rotational speeds
D_b	bit diameter (in)
D_h	diameter of the housing (in)
D_p	ECD_p-P_p(psi)
d_s	diameter of the shaft pitch circle (in)
ECD	equivalent circulating density (ppg)
ECD_p	pressure in psi exerted by an ECD in ppg
E_m	mechanical efficiency of new bit
F_i	internal force of drill string produced by bottom hole WOB_b (lbf)
F_{i1}	internal force of drill string at the upper end produced by bottom hole WOB_b (lbf)
F_{i2}	internal force of drill string at the lower end produced by bottom hole WOB_b (lbf)
F_n	the resultant force acting at the contact point (lbf)
HHP	hydraulic horsepower (hp)
i	winding ratio
L_m	length of the PDM (in)
L_s	total length of the seal line (in)
MHP	mechanical horsepower provided by PDM (hp)
MSE	mechanical specific energy (psi)
n	number of shaft lobes of the motor (winding number)
n_s	number of mud motor stage
ΔP_b	pressure drop across the bit (psi)
P_h	pitch of the housing (in)
ΔP_m	differential pressure across the PDM (psi)
P_p	pore pressure (psi)
Q	flow rate (gal/min)
q	PDM unit displacement (gal/ rev)

Q_{slip}	Mud slip flow through the PDM (gal/min)
ROP	rate of penetration (ft/h)
RPM	bit rotating speed (rpm)
RPM_{ideal}	ideal PDM rotary speed (rpm)
RPM_s	bit rotary speed provided by surface (rpm)
RPM_m	PDM output rotary speed (rpm)
T	torque at bit (ft-lbf)
ΔT	torque loss (ft-lbf)
T_{ideal}	ideal PDM output torque (ft-lbf)
T_s	torque at bit provided by surface (ft-lbf)
T_m	PDM output torque (ft-lbf)
UCS	unconfined compressive strength (psi)
V	volume of rock drilled in one hour (ft-in^2)
W_t	total mechanical work done by the bit in one hour (ft-lbf)
W_V	mechanical work required to break the rock drilled in one hour (ft-lbf)
WOB	weight on bit of surface measurement (lbf)
WOB_b	bottom hole actual weight on bit (lbf)
y	contact semi-width (in)
α	helix angle of seal line (degree)
β	coefficient of hydraulic horsepower
δ	clearance of the slip passage (in)
μ_b	bit-specific coefficient of sliding friction
μ_s	coefficient of friction of drill string
μ	viscosity of mud (cp)
γ	well inclination (rad)
$\Delta\gamma$	additional well inclination (rad)
γ_b	inclination of the bottom hole (rad)
ϕ	rock internal angle of friction (degree)
Γ_i	configuration correction factor
η	efficiency of PDM

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