Performance, simulation and field application modeling of rollercone bits

Behrad Rashidi *, Geir Hareland 1, Zebing Wu

Department of Chemical & Petroleum Engineering, University of Calgary, Calgary, Alberta, Canada T2N 1N4

ABSTRACT

Drilling simulation technology has been used extensively to optimize drilling operations so as to minimize the associated costs and risks. Optimum bit types and designs with corresponding drilling parameters can be recommended utilizing a simulator with rate of penetration (ROP) models. There have been several attempts to develop ROP models that can deliver the most reliable outputs, required for the pre-planning and post analysis applications, using various sets of drilling parameters. However, due to the existing modeling complexities, these attempts have not been successful. In this study, a new ROP model is developed for the rollercone bits, which properly integrates the effect of main drilling parameters as well as cutting structure of the bit. The model is mathematically derived based on the mechanism of single cutter–rock interaction, and calibrated utilizing sets of full scale laboratory data. Also, the bit wear effect for simulating accurate rock strength and ROP values is included in the analysis using a previously published model. One of the most important features of the newly introduced ROP model is that it can be easily inverted to generate accurate rock strength values using offset and/or real-time field data. This unique characteristic of the ROP model makes it a valuable candidate for drilling simulation studies to optimize drilling operations in the most cost effective manner. The verification of the introduced ROP model is performed through series of simulation analysis and comparing the generated rock strength logs to the outputs of a commercially available drilling simulator. The comparison of the results obtained from the simulator and the ROP model as well as field data has been quite encouraging which signifies the application of the developed model in determining the best case scenario for planning and/or drilling of future wells with lowest possible expenditures.

© 2015 Elsevier B.V. All rights reserved.

1. Introduction

In oil and gas industry, it has been well recognized that the associated time and cost of drilling wells is a major part of the total field development expenses. One of the main objectives of the entire well development plans is to minimize the overall well cost in compliance with safe operations and environmental regulations. Drilling rate is one of the key parameters in optimizing the performance of the operations through reducing the rotating time of the bit. Accordingly, drilling rate models play an important role in improving drilling performance using available offset well data and/or in real-time drilling.

Extensive studies have been performed to develop comprehensive ROP models for the commonly used rollercone bits considering the effect of associated drilling and bit design parameters. However, due to the existing modeling restrictions, as outlined below, previous attempts have not been successful and never led to develop a practical model.

- Mathematically modeling forces applied to the formation by bit cutters.
- Mathematically modeling generated rock volume by each single cutter as well as estimating cumulative generated cutting volume considering bit rotation.
- Taking into account integrated effect of operational and bit design parameters.
- Developing invertible ROP models that can be used to estimate formation strength values using any sets of drilling parameters.

Therefore, the developed ROP models that integrate the above-mentioned parameters/effects can be utilized as the core engine of
drilling simulators for conducting drilling optimization studies. Available offset well data can be used as the input to drilling simulators in order to generate apparent rock strength logs (ARSL) and/or formation drillability over the well interval. Rock strength logs can also be generated with a good accuracy using log data. The trends obtained from log data could be useful in verifying correct rock strength variations generated by the ROP models specially when sufficient drilling offset information is not accessible.

The main goal of conducting drilling simulation studies is to achieve lowest cost of the well through optimization analysis that includes recommending optimum sets of bit types, designs as well as corresponding operational parameters and bit pull depths while minimizing drilling problems (Nygaard et al., 2002). Also, real-time transmission and analysis of drilling data, from a remote server to an office location, plays an important role in optimizing drilling operations. Drilling engineers can provide expert opinions to rig personnel, thus increasing drilling efficiency as well as reducing the associated risks (Rashidi et al., 2010).

The primary objective of this study is to develop a new, comprehensive and practically applicable ROP model for application use in a simulator environment for drilling simulation studies, pre-planning, real-time and post analysis operational mode utilizing rollercone bits.

2. Overview and background

2.1. Single cutter–rock interaction

The cutter–rock interaction is the preliminary area of study in analyzing drilling performance of rollercone drill bits. There exist several shortcomings to this area which is mainly due to the complexity in rock failure phenomenon as well as modeling the contact forces during digging action of the bit cutters.

Several models have been introduced to investigate rock breakage angle of the rock chips using a force balance system. Hill et al. (1947) and Outamans (1960) introduced their rock breakage models for ductile materials which could not be applied in brittle materials with much accuracy. Paul and Sikarskie (1965) proposed a theoretical study for a static wedge penetration model based on Mohr-Coulomb failure criterion. Their theory expressed rock failure mechanism through crushing and chipping phases as shown in Fig. 1. The positive slope lines represent the elastic deformation or crushing phases whereas chip formations are characterized by the negative slope lines in each cycle. Dutta (1972) put forth a theory explaining rock breakage phenomenon as a momentarily release of strain energy including both crushing and chipping events. It has been then shown that the rock breakage phenomenon can be considered as a brittle failure characterized by fractures as a result of cutter’s indentation. Cheatham (1985) conducted a study on the amount of force required for a wedge shaped cutter to penetrate into the rock. In his model, the rock underneath cutters was assumed to be isotropic and homogeneous in a rigid plastic state which satisfies yield condition in Mohr–Coulomb theory of failure. The process of rock failure under indentation of cutters includes build-up of the stress field, formation of a zone of inelastic deformation and development of a crater respectively.

2.2. Rollercone bit modeling

Several drilling models have been introduced over the years to express rock-bit interaction of rollercone bits as a function of associated drilling and bit design parameters. Primary models were published by Galle and Woods (1960) and Morlarn (1961) in soft formations introduced ROP models merely as a function of WOB and RPM. Maurer (1962) proposed his model as a function of operating parameters and rock strength but it failed to predict ROP response to the applied low WOB. Bingham (1965) suggested a new ROP model based on limited laboratory data with the assumption of negligible threshold weight on bit (WOB0) and rotary speed exponent of one despite the fact that ROP response to increasing rotary speed diminishes at high RPM values. Few years later, Bourgoyne and Young (1973) suggested a drilling rate model considering the effect of several drilling variables on ROP. This model was derived merely for unsealed roller bearing milled tooth bits in vertical wells and the effect of parameters such as WOB, RPM, bit tooth wear and others were assumed to be independent of one another (Ettehadi, 2007). In 1981, Warren introduced a new ROP model that integrated the effects of the mechanical and lithological parameters. The model was developed using dimensional analysis and generalized response curves for the best fit using laboratory data. The results have revealed that generated rock volume by a single tooth is proportional to the tooth force squared and inversely proportional to the rock strength squared. His model was later modified by Rampersad et al. (1994) for taking into account bit wear and chip hold down effects. Although the predicted ROP values match field and laboratory data using this model, it is not always possible to obtain positive rock strength values utilizing the inverted model. In 1995, Ma developed a computer simulation program based on rock-bit interaction which reflected the effect of cutters structure on ROP. This model did not integrate the effect of rotary speed variations in simulating ROP values and is also very complex and time consuming to run, so it could not be used in drilling simulation studies especially in real-time analysis.

3. Technical approach

3.1. Rollercone bit performance modeling

Development of a new, accurate and applicable drilling rate model for rollercone bits is one of the keys to get valuable outcomes from drilling simulation studies. The model should have the capability of directly estimating ROP as well as approximating rock strength values utilizing the inverted model with known parameters. Furthermore, the model should properly reflect the effect of changes in bit design and cutters’ geometry for various bit IADC codes.

In this study, a new comprehensive and practical ROP model for rollercone bits is developed based on the approach introduced by Evans and Murrell (1962) and further modified by Ma et al. (1995). A single cutter performance model was first established based on the experimental data and the ROP model was then introduced by
integrating single cutter performance over the bit area. Finally, the newly developed model was calibrated and verified utilizing laboratory and field scale data.

3.1 Single cutter performance modeling

The indentation of a single insert as well as analysis of forming rock chips through rock fracturing occurrence are used as the beginning step in performance modeling of rollercone bits. In this study, mechanical modeling of forces and geometrical modeling of rock breakage craters are used to analyze cutter–rock interaction.

3.1.1.1. Wedge penetration model. Formation of a chip as a result of indenting a wedge shape cutter into a rock specimen is a continuous process including crushing and chipping phases. For the crushing phase, rock is fragmented in the area surrounding the wedge as the wedge advances and causes the elastic stress to build up. A chip will then form along the fracture surface after a certain level of penetration is reached. Fig. 2 represents formation of the \((i+1)\)th chip after the \((i)\)th chip has been generated.

In this theory, the shear stress along the fracture line is proportional to cohesive rock strength, which satisfies the Mohr-Coulomb yield criterion. Moreover, the rock breakage/failure angle \(\psi\), which is a characteristic property of the formation, can be represented as a function of rock internal friction angle \(\phi\) as shown in Fig. 3:

\[
\psi = \frac{1}{2} \left( \frac{\pi}{4} - \frac{\phi}{2} \right)
\]  

3.1.2. ROP modeling of rollercone bits

In this study, a new and comprehensive ROP model is derived directly based on the rock craters fractured by a single insert. The work behavior of each insert includes both crushing and shearing, which represents the actual movement of inserts on the rollercone bits. The model is initially verified using following information:

- Outputs of an available complex 3D design evaluation program (Ma et al., 1995), for various bit IADC codes.
- The result of the single-row insert indentation test conducted by Kingdream in China (Z. Wu, Personal communication, June 2010). Figs. 4 and 5 show the apparatus as well as the data collection system used to run the test.

The complex 3D model is not practical to be used in drilling simulation and optimization studies as it is slow, detailed design parameters are required, and missing key functionalities such as failing to reflect the integrated effect of the associated key parameters on the rate of penetration. However, it can be used to accurately integrate the effect of changes in bit designs and cutters’ geometry including static bit wear and cutters structures on the proposed model. The results of the 3D modeling are used to
establish the ROP model for the perfect cleaning condition at the bit indicating that cuttings are removed from underneath the bit as fast as they are generated.

The volume of the generated craters by each individual insert are also directly linked to the applied normal drilling parameters and depth of cut during indentation of the cutters. The portion of the crater, which is removed directly by the insert, is the “plastic part”. The second or brittle part of the crater, which is known as conical section, is removed as a result of vertical and lateral crushing, as shown in Fig. 6.

Experimental studies have revealed that the amount of force, which is applied by each individual cutter to the formation, is linearly proportional to the depth of cut, wedge length in contact with the rock, and rock strength (Evans and Murrel, 1962). Further studies have also shown that the applied force to a single cutter can be expressed as a function of the projected area of the cutter in contact with the formation, cutter’s indentation depth and the rock properties, such as rock strength, in power form (Ma et al., 1995).

The approach which is adopted in this study is the modified version of the aforementioned methods assuming that the force, \( F \), can be expressed in terms of rock properties and cutter’s geometry as presented in Fig. 7:

\[
F = a_1 \cdot S \cdot h^3 \cdot CCS^3 \cdot (f + \tan \theta)
\]

where \( a_1, b_1, c_1 \): constants.

On the other hand, it has been shown that cross section area of an unworn cutter can be represented as a function of cutter’s height as expressed below (Hareland et al., 2011):

\[
S = r_1 h^2 + r_2
\]

where \( r_1, r_2, r_3 \): constants.

The constants of the above equation vary for each rollercone bit IADC code (i.e. 111, 437, 517, etc.). Fig. 8 shows three common types of cutters (Conical, Chisel and Scoop) which are mostly used in manufacturing rollercone bits. The cross section areas of these inserts are also calculated and presented as a function of truncated depth of the inserts with a good accuracy as presented in Fig. 9. Therefore, the applied force on a single cutter can be expressed as

\[
F = a_1 h^3 \cdot CCS^2 \cdot (f + \tan \theta)
\]

\( a_1, b_1, c_1 \): constants.

Moreover, the friction between the cutters and the rock (\( f \)) is assumed to be negligible, due to dynamic nature of insert–rock interaction while drilling, as a simplifying assumption for further modeling purposes.

The resultant reactive force (\( F \)) for the inserts in contact with the bottom rock is equivalent to the applied WOB and can be presented as

\[
WOB = n_t F
\]

where \( n_t \): average number of inserts in contact with the bottom rock.

Moreover, in this study, the crater volume generated by each single insert is assumed to be conical, as depicted in Fig. 10:

\[
V_{crater} = \frac{1}{3} \pi r_{crater}^2 h
\]

Also, rock failure angle (\( \psi \)) can be expressed mathematically as

\[
\tan \psi = \frac{h}{r_{crater}}
\]

Therefore

\[
V_{crater} = \frac{1}{3} \pi h^3 \tan \left( \frac{\pi}{2} - \psi \right)^2 h
\]

On the other hand, ROP is defined as the ratio of the generated rock volume by the bit cutters over the bit area per revolution of the bit as presented below:

\[
ROP = \frac{V_{crater} \cdot n_t \cdot RPM}{\text{Area}_{bit}}
\]

By substituting Eqs. (4), (5), (6) into Eq. (9) and demonstrating bit area in terms of bit diameter (\( D_b \)), ROP can be shown as below:

\[
ROP = \frac{K \cdot m \cdot n_t \cdot WOB \cdot RPM}{CCS \cdot \tan \theta \cdot D_b^2 \cdot \tan \psi}
\]

where \( k, a, b, c, d \): constants.

The variables “\( m \)” and “\( n_t \)” are related to many factors and have been determined using the 3D complex simulation program for various bit IADC codes (Wu et al., 2005). The program can simulate the working behavior of the cutters according to the load equilibrium system. Thus, instantaneous loads on each insert and cone as well as cutters and bottom hole pattern can be simulated as schematically shown in Fig. 11.

\[
m = f(WOB, RPM, Bittype, Rock, etc.) \quad (11)
\]

\[
n_t = f(WOB, RPM, Bittype, Rock, etc.) \quad (12)
\]
3.1.2.1. Rock failure angle analysis. As presented in Eq. (1), rock breakage angle ($\psi$) can be expressed solely in terms of rock internal friction angle ($\phi$). On the other hand, rock failure angle is the main input of the developed ROP model and must be known for performing simulation studies. The required information for indicating rock failure angle is not always available specially for conducting performance analysis using field data. Therefore, In this study, the following approach was adopted, with reference to Fig. 3, to express the rock breakage angle ($\psi$) as a function of depth of cut ($h$) and half-wedge angle of the cutters ($\theta$).

As per Fig. 3, half-wedge angle of the crushed rock mass ($\beta$) can be presented as

$$\tan(\beta) = \frac{r_{crater}}{d} \quad (13)$$

$r_{crater}$: radius of the generated crater after rock failure happens (m), $d$: total rock cutting depth (m).

Moreover,

$$\tan(\theta) = \frac{r_{crater}}{h} \quad (14)$$

$$d = a_1 h^{b_1} \quad (15)$$

$a_1, b_1$: constants.

Combining Eqs. (13)–(15) will result in

$$\tan(\beta) = \tan(\theta) a_1 h^{b_2} \quad (16)$$

$a_2, b_2$: constants.

Furthermore, depth of cut ($h$) has been shown that can be expressed as a function of rate of penetration (ROP) per revolution of the bit (RPM). Thus

$$\tan(\beta) = \tan(\theta) a_1 \left( \frac{ROP}{RPM} \right)^{b_2} \quad (17)$$

In addition, it can be implied that the rock breakage angle ($\psi$) can be stated in terms of rock internal friction angle and half-wedge angle of the crushed rock mass ($\beta$) as

$$\psi = \frac{\pi}{4} - \frac{\beta + \phi}{2} \quad (18)$$

Hence, Eqs. (1) and (18) will imply

$$\beta \cong 2\psi \quad (19)$$

Therefore

$$\tan(2\psi) = \tan(\theta) a_1 \left( \frac{ROP}{RPM} \right)^{b_2} \quad (20)$$

The above equation shows that the rock breakage angle is a function of half-wedge angle of the cutter ($\theta$) and the depth of cut ($h$) in the power form. This relationship does not violate the fact that the rock failure angle ($\psi$) is only a characteristic property of the rock and it does not change as a function of operational and
design parameters. In fact, any variation in the cutter’s wedge angle will change the depth of cut (indentation) of the cutter and will not affect the magnitude of the rock failure angle.

In addition, it has been determined that the range at which the rock breakage angle may vary can roughly be estimated as follows (Dutta, 1972):

\[ 0 \leq \psi \leq 22 \]

Thus, one can simply correlate \( \tan(2\psi) \) versus \( \tan(\psi) \) as shown below:

\[ \tan(2\psi) = 2.3 \tan(\psi)^{1.05} \]  

Therefore, by substituting Eqs. (20) and (21) into Eq. (10), ROP model can be presented independent of the rock breakage angle as below:

\[ ROP = K \frac{mn_i WOB^a RPM^b}{CCS^c \tan \theta^d D_B^{2}} \]  

(22)

Here, \( K, a, b, c, d \): constants.

### 3.1.2.2. Modeling the hole size effect

Hole size or bit diameter \( D_B \) is one of the main inputs of the drilling rate model, which can significantly influence the performance of rollercone bits. As indicated in above equation, larger bit diameter reduces ROP if other operational and bit design parameters are kept constant. However, according to Mensa and Fear (2001), ROP is not always increasing as the bit diameter is reduced. The results, which are also accepted by the industry as a valid functionality, showed that ROP increases with reduction in bit diameter up to the certain bit size and start decaying afterwards as depicted in Fig. 12. The optimum bit diameter to reach maximum bit performance has been reported to be approximately 8.5°. This has also been confirmed through laboratory and field results (Warren, 1981).

Therefore, herein, the developed ROP model by Warren (1981) for the rollercone bits was utilized to generate the following functionality of ROP for various bit diameters \( D_B \). The model is normalized to generate a maximum ROP at the 8.5° bit diameter. The constants of the model are also obtained and tabulated in Table 1 through multiple regression analysis.

\[ f_B(D_B) = r_1 D_B^4 + r_2 D_B^3 + r_3 D_B^2 + r_4 D_B + r_5 \]  

(23)

\[ f_B(D_B): \) bit diameter function, \( D_B: \) bit diameter (m), \( r_1, r_2, r_3, r_4, r_5: \) constants.

Finally, the developed ROP model can be presented as follows with properly taking into account the hole size effect.

\[ ROP = K \frac{mn_i WOB^a RPM^b}{CCS^c \tan \theta^d f_B(D_B)} \]  

(24)

### 3.1.2.3. Calibration of the newly developed ROP model

The newly developed ROP model can be used for predicting rate of penetration or/and apparent rock strength log after it is calibrated using experimental data. Each bit IADC code requires specific laboratory data to calibrate the ROP model so it can be used for performance analysis of the same bit through implementing various drilling scenarios. Since the ROP model is developed for the perfect cleaning condition at the bit, only clean ROP values are selected from laboratory data sets which are characterized by the semi-linear functionality of ROP to the applied WOB.

Due to the limited availability of laboratory data for various bit IADC codes, the constants of the model were determined herein through multiple regression analysis for bit IADC 517 in metric units as tabulated in Tables 2 and 3.

Fig. 13 also shows a good match between the calculated ROP values by the model and corresponding measured ROP values in the laboratory for a different set of experimental data utilizing rollercone bit IADC 517.

### 3.1.2.4. Rock confinement effect on rock unconfined compressive strength

Analysis of bit performance based on generated rock

---

### Table 1

Calculated constants of the bit diameter function using multiple regression analysis.

<table>
<thead>
<tr>
<th>Constants of ( f(D_B) ) function</th>
<th>Numerical value (metric system)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_1 )</td>
<td>106.4</td>
</tr>
<tr>
<td>( r_2 )</td>
<td>–33.3</td>
</tr>
<tr>
<td>( r_3 )</td>
<td>–34.6</td>
</tr>
<tr>
<td>( r_4 )</td>
<td>14.4</td>
</tr>
<tr>
<td>( r_5 )</td>
<td>–0.4</td>
</tr>
</tbody>
</table>

---

### Table 2

Calculated constants of the ROP model for bit IADC 517.

<table>
<thead>
<tr>
<th>Constants</th>
<th>Numerical values</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K )</td>
<td>0.17</td>
</tr>
<tr>
<td>( a )</td>
<td>1.33</td>
</tr>
<tr>
<td>( b )</td>
<td>0.64</td>
</tr>
<tr>
<td>( c )</td>
<td>0.5</td>
</tr>
<tr>
<td>( d )</td>
<td>0.4</td>
</tr>
</tbody>
</table>

---

### Table 3

Laboratory data sample used to obtain the constants of the ROP model (IADC 517).

<table>
<thead>
<tr>
<th>WOB (T)</th>
<th>ROP (m/h)</th>
<th>RPM</th>
<th>CCS (MPa)</th>
<th>( D_B ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.45</td>
<td>3.42</td>
<td>60</td>
<td>58.39</td>
<td>0.216</td>
</tr>
<tr>
<td>9.60</td>
<td>4.22</td>
<td>60</td>
<td>58.37</td>
<td>0.216</td>
</tr>
<tr>
<td>12.66</td>
<td>6.57</td>
<td>60</td>
<td>58.32</td>
<td>0.216</td>
</tr>
<tr>
<td>15.79</td>
<td>7.76</td>
<td>60</td>
<td>58.29</td>
<td>0.216</td>
</tr>
<tr>
<td>18.89</td>
<td>8.82</td>
<td>59</td>
<td>58.32</td>
<td>0.216</td>
</tr>
<tr>
<td>6.37</td>
<td>2.83</td>
<td>122</td>
<td>113.53</td>
<td>0.216</td>
</tr>
<tr>
<td>9.54</td>
<td>5.19</td>
<td>122</td>
<td>113.53</td>
<td>0.216</td>
</tr>
<tr>
<td>12.69</td>
<td>7.10</td>
<td>122</td>
<td>113.51</td>
<td>0.216</td>
</tr>
<tr>
<td>15.79</td>
<td>8.87</td>
<td>122</td>
<td>113.49</td>
<td>0.216</td>
</tr>
<tr>
<td>18.82</td>
<td>11.59</td>
<td>122</td>
<td>113.53</td>
<td>0.216</td>
</tr>
</tbody>
</table>
Strength logs using drilling rate models has become a standard practice in the oil and gas industry. The rock strength term in ROP models represents the confined rock compressive strength. This term cannot be used directly in drilling simulations and optimization studies due to the presence of rock confinements. Basically, confinement pressure increases rock resistance to breakage, which is evident while testing a sample in the laboratory under the applied loads. Therefore, rock confinement effect must be eliminated from the generated rock strength values using inverted ROP models (CCS). Rampersad et al. (1994) proposed the following correlation that relates confined rock compressive strength (CCS) to unconfined rock compressive strength (UCS) as a function of confinement pressures.

\[
\text{CCS} = \text{UCS}(1 + a_i P_e^{b_i})
\]

CCS: confined rock compressive strength (MPa), UCS: unconfined rock compressive strength (MPa), \(P_e\): confinement pressures (MPa), \(a_i, b_i\): coefficients.

The constants of the above equation are varied depending upon the rock permeability as tabulated in Table 4.

Also, the confinement pressure \(P_e\) can be defined as the difference between the bottom hole pressure (i.e.: hydrostatic pressure of the drilling fluid) and pore pressure. The latter is the pressure of the fluid inside the rock, particularly for permeable formations, as shown below.

\[
P_e = P_{BHP} - P_p
\]

### Table 4

<table>
<thead>
<tr>
<th>Coefficients</th>
<th>Permeable rocks</th>
<th>Impermeable rocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_i)</td>
<td>0.24</td>
<td>0.24</td>
</tr>
<tr>
<td>(b_i)</td>
<td>0.38</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Fig. 13. Comparison between calculated and reported experimental ROP values utilizing the developed ROP model.

Fig. 14. Flow chart showing steps for estimating rock unconfined compressive strength utilizing new ROP model including bit wear effect.
Hydrostatic pressure \( P_{\text{hydrostatic}} \) (MPa), TVD: true vertical depth (m), MW: mud weight (kg/m³).

\[
P_{\text{hydrostatic}} = 9.8 \times 10^{-6} \cdot \text{TVD} \cdot \text{MW}
\]

\( k, a, b, c, d \): constants.

The iteration process utilizing wear function is also outlined below as well as schematically depicted in Fig. 14.

- Select an arbitrary low initial value for the bit wear constant \( C_i \).
- Calculate rock strength (CCS) value using the inverted ROP model for the first point of the drilled section with no bit wear \( \Delta BG = 0 \).
- Calculate \( \Delta BG \) for each point using the calculated CCS values from previous points for the entire bit run section.
- Check with a tolerance that final bit wear, for the last meter where bit was pulled \( \Delta BG_{\text{out}} \), matches the reported bit wear out as shown below:

\[
\left| \Delta BG_{\text{out}} - \Delta BG_{\text{in}} \right| < 0.001
\]

- Repeat the iterations with new modified bit wear constant value until both calculated and reported bit wear outs match up.

\[
P_{\text{new}} = C_i \frac{\left| \Delta BG_{\text{out}} - \Delta BG_{\text{in}} \right|}{\left| \Delta BG_{\text{out}} - \Delta BG_{\text{in}} \right|}
\]

- The final bit wear constant can then be utilized to obtain unconfined rock compressive strength (UCS) for the drilled interval.

In the area where offset well data are available, the apparent rock strength log (ARSL) or UCS can be generated for the entire well utilizing this method. The apparent rock strength log (ARSL) is the main input for the simulation studies of the upcoming wells in the same area. It gives the drilling engineers the ability to simulate bit performance using operating parameters including different bit pull depths for different drilling scenarios. This method has already been successfully used in various oil fields in western Canada (Fazaelizadeh et al., 2010).

Fig. 15 depicts a schematic representation of the development steps of the new ROP model introduced in this study.

**4.2. Verification of the newly developed ROP model**

The verification of the newly developed ROP model was performed utilizing offset well data to:
Generate UCS meter by meter logs for an specific area and compare the results as the first verification part.

Utilize the generated UCS logs to calculate ROP values for another well drilled in the same area and compare the calculated ROP results with the recorded ROP values in the field as the second verification part of the model.

Moreover, the outputs of a drilling simulator (Drops) (Bratli et al., 1997) as well as the generated rock strength logs utilizing log data (Andrews et al., 2007), as shown below, were used for further model’s verifications.

\[
UCS = \frac{K_1(1 - \phi_{N})^{0.18}}{(\Delta t - 130)^{K_2}}
\]

\[
f = \frac{(1 - \phi_{N})^{0.18}}{1 - (\phi_{N})^{0.18}}
\]

\[\phi_N: \text{neutron porosity (fraction), } \phi_{N-ss}: \text{neutron porosity of pure sandstone formation (fraction), } \phi_{N-sh}: \text{neutron porosity of pure shale formation (fraction), } \Delta t: \text{sonic travel time (ms/m), } K_1, K_2: \text{constants.}\]

Since the ROP model is developed for the perfect cleaning condition, the bit run sections with sufficient hydraulic energy at the bit from offset data sets were selected for conducting simulation analysis.

First part of the analysis was performed by comparing the calculated rock strength values obtained for bit run sections of two adjacent wells (wells A and B) in central Alberta, drilled with the same bit type after the formation tops have been correlated, as shown in Fig. 16. To have a basis for further analysis, the outputs of a drilling simulator (Drop’s) were plotted against the calculated values obtained from the model as presented in Figs. 17 and 18. The results confirmed that the ROP model predictions are accurate enough and are comparable to the available outputs of the simulator.

For the second part of the verification, the generated rock strength log(s) for a bit run of well A was used to estimate the ROP values of another bit run from well B that was drilled through similar formations with the same bit. These results were then compared with the field reported ROP values as shown in Fig. 19. There is an encouraging match between the calculated and reported ROP values which is also indicated by the root mean square error (RMSE) exponent of approximately 10 MPa.
To ensure of the accuracy of the model as well as having an additional verification tool, the rock strength values were also generated utilizing log data for a selected bit run section of well A and compared with the generated UCS values obtained from the developed ROP model as shown in Fig. 20.

5. Highlights and conclusions

The time spent with bit on bottom is one of the main parameters in evaluating performance of drilling operations. Proper selection of operational parameters, bit types and designs prior to drilling a well will help reduce on bottom drilling time and optimize drilling operations accordingly.

The newly and comprehensively developed ROP model in this study is an stepping stone towards analyzing performance of rollercone drill bits through recommending best parameters required for enhancing drilling performance of a well.

The summary of the conclusions that can be drawn from this study are as follows:

- The applied force by each single cutter of rollercone bits to the rock is a direct and non-linear function of rock strength, depth of cut, horizontal projected area and wedge angle of the cutter.
- Average number of cutters in contact with formation per revolution of the bit can be represented by depth of cut which is the ratio of drilling rate (ROP) to rotational speed of the bit (RPM).
- Rock breakage angle is a function of half wedge angle of the bit cutters ($\theta$) as well as the depth of cut.
- The potential application of the developed ROP model was shown to be encouraging when comparing simulated rock strength/ROP values with the outputs of drilling simulator as well as reported values from the field.
- The newly developed ROP model and simulation method can also be utilized in real-time drilling for performance monitoring of rollercone bits and providing constructive recommendations on the fly required for minimize potentially occurring drilling problems and achieving maximum drilling efficiency.
Fig. 20. Comparison between calculated UCS values using new ROP model and generated rock strength values utilizing log data for a bit run section of well A (RMSE: ~45 MPa)

Acknowledgments

I would like to gratefully acknowledge Prof. G. Hareland and his enthusiastic supervision throughout this work. I also wish to express my sincere appreciation to Dr. Z. Wu for all the technical support he provided during my study.

Special thanks to Nexen Energy ULC., British Gas, Talisman Energy, Pason, NSERC, and University of Calgary for providing technical data, financial support, and great opportunities to make this work a success.

References


