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Performance, simulation and field application modeling of rollercone bits

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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.

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

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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.

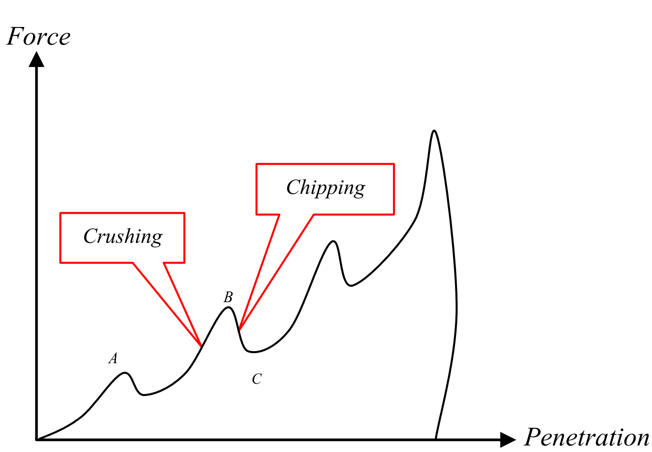

Fig. 1. Schematic representation of experimental cutter force to rock penetration.

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 (WOB_0) 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 Murrel (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.

3.1.1 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 (ψ), which is a characteristic property of the formation, can be represented as a function of rock internal friction angle ($\emptyset$) as shown in Fig. 3:

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

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

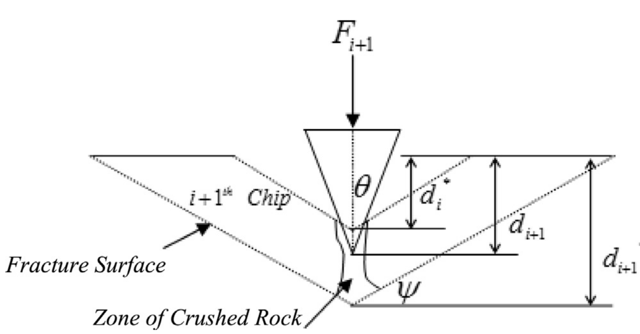

Fig. 2. Schematic representation of single wedge/tooth penetration model (Paul and Sikarskie, 1965).

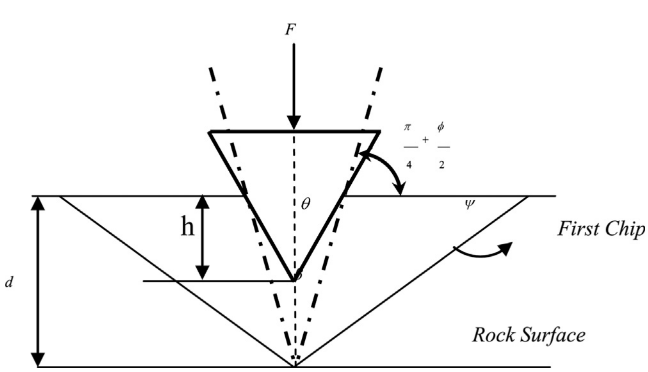

Fig. 3. Schematic representation of a chip created by indentation of a single wedge cutter (Dutta, 1972).

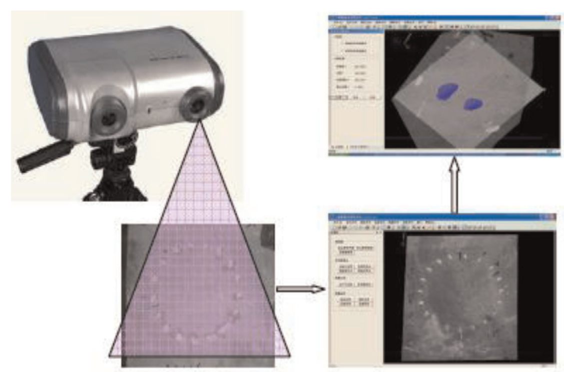

Fig. 4. 3D scanning camera system used to capture the geometry of the generated craters (Hareland et al., 2010).

Fig. 5. Single-row insert work piece used to run the indentation test (Hareland et al., 2010).

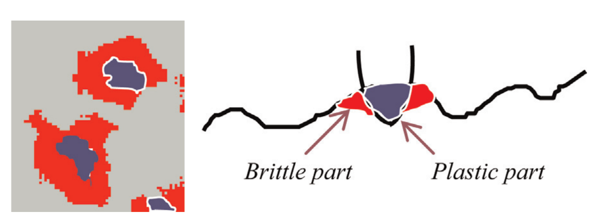

Fig. 6. Schematics of rock craters generated by inserts.

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:

$$F = a.\ S.\ h^b.\ CCS^c.\ (f + \tan\theta) \tag{2}$$

a, b, c: 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):

$$S = r_1 \cdot h^{r_2} + r_3 \tag{3}$$

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

$$F = a_1.\ h^{b_1}.\ CCS^c.\ (f + \tan\theta) \tag{4}$$

a_1, b_1, c: 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

$$WOB = n_t.\ F \tag{5}$$

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:

$$V_{crater} = \frac{1}{3}\pi^* r_{crater}{}^2{}_* h \tag{6}$$

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

$$\tan(\psi) = \frac{h}{r_{crater}} \tag{7}$$

Therefore

$$V_{crater} = \frac{1}{3}\pi^*\left(h^* \tan\left(\frac{\pi}{2} - \psi\right)\right)^{2*} h \tag{8}$$

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:

$$ROP = \frac{V^*_{crater} n_t^* RPM}{Area_{bit}} \tag{9}$$

By substituting Eqs. (4), (5), (8) into Eq. (9) and demonstrating bit area in terms of bit diameter (D_B), *ROP* can be shown as below:

$$ROP = K.\ \frac{m^* n_t^* WOB^{a*} RPM^b}{CCS^{c*} \tan\theta^{d*} D_B{}^{2*} \tan^2\psi} \tag{10}$$

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 craters and bottom hole pattern can be simulated as schematically shown in Fig. 11.

$$m = f(WOB,\ RPM,\ Bittype,\ Rock,\ etc.\ ) \tag{11}$$

$$n_t = f(WOB,\ RPM,\ Bittype,\ Rock,\ etc.\ ) \tag{12}$$

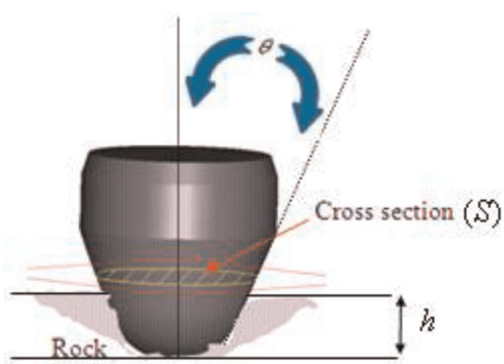

Fig. 7. Simple schematic of a single insert indentation presenting cross section area of cutter at the indentation depth as well as cutter half wedge angle (Hareland et al., 2011).

Fig. 8. Cross section area of the common cutter types as a function of height of cutters (Hareland et al., 2011).

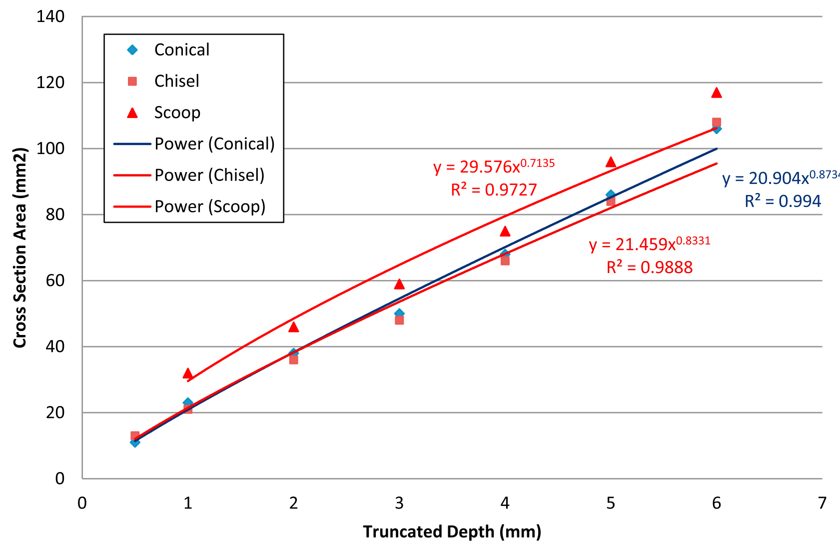

Fig. 9. Relationship between cross section area and truncated depth of three common insert types (Hareland et al., 2011).

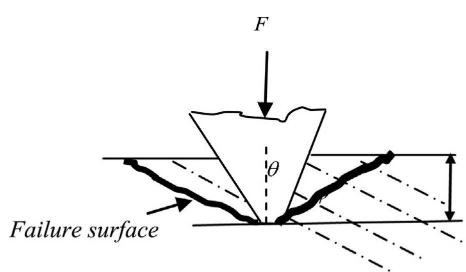

Fig. 10. Simple schematic of a formed conical crater as a result of single insert indentation.

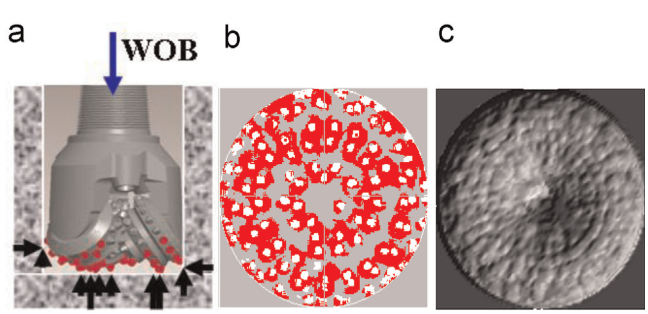

Fig. 11. (a) Load equilibrium of cutters on bottom hole, (b) schematic of generated craters by inserts and (c) 3D view of bottom hole pattern (Hareland et al., 2010).

3.1.2.1. Rock failure angle analysis. As presented in Eq. (1), rock breakage angle (ψ) can be expressed solely in terms of rock internal friction angle ($\emptyset$). 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 (ψ) as a function of depth of cut (h) and half-wedge angle of the cutters (θ).

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

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

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

Moreover,

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

$$d = a_{1*}h^{b_1} \tag{15}$$

a_1, b_1: constants.

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

$$\tan(\beta) = \tan(\theta)^{*}a_2^{*}h^{b_2} \tag{16}$$

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

$$\tan(\beta) = \tan(\theta)^{*}a_2^{*}\left(\frac{ROP}{RPM}\right)^{b_2} \tag{17}$$

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

$$\psi = \frac{\pi}{4} - \frac{\beta + \phi}{2} \tag{18}$$

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

$$\beta \cong 2_{*}\psi \tag{19}$$

Therefore

$$\tan(2\psi) = \tan(\theta)^{*}a_2^{*}\left(\frac{ROP}{RPM}\right)^{b_2} \tag{20}$$

The above equation shows that the rock breakage angle is a function of half-wedge angle of the cutter (θ) and the depth of cut (h) in the power form. This relationship does not violate the fact that the rock failure angle (ψ) is only a characteristic property of the rock and it does not change as a function of operational and

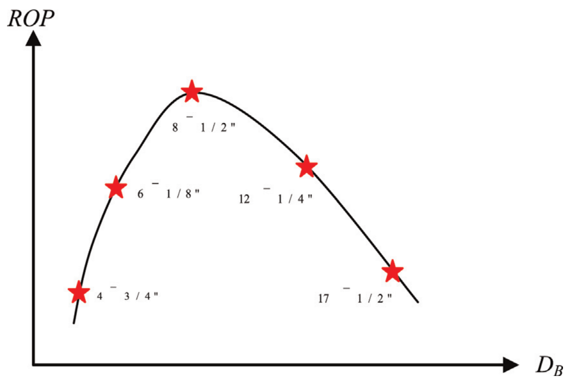

Fig. 12. *ROP* sensitivity to the hole size (schematic).

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):

$$0 \le \psi \le 22$$

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

$$\tan(2\psi) = 2.3 * \tan(\psi)^{1.05} \tag{21}$$

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

$$ROP = K * \frac{m * n_t * WOB^{a} * RPM^{b}}{CCS^{c} * \tan\theta^{d} * D_B^{2}} \tag{22}$$

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.

$$f_B(D_B) = r_1 . D_B^{4} + r_2 . D_B^{3} + r_3 . D_B^{2} + r_4 . D_B + r_5 \tag{23}$$

$f_B(D_B)$: 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.

$$ROP = K * \frac{m * n_t * WOB^{a} * RPM^{b}}{CCS^{c} * \tan\theta^{d}} * f_B(D_B) \tag{24}$$

k, a, b, c, d: constants.

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 confinements 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.

Constants of $f_B(D_B)$ function	Numerical value (metric system)
r_1	106.4
r_2	−33.3
r_3	−34.6
r_4	14.4
r_5	−0.4

Table 2
Calculated constants of the *ROP* model for bit IADC 517.

Constants	Numerical values
K	0.17
a	1.33
b	0.64
c	0.5
d	0.4

Table 3
Laboratory data sample used to obtain the constants of the *ROP* model (IADC 517).

WOB (T)	*ROP* (m/h)	*RPM*	*CCS* (MPa)	D_B (m)
6.45	3.42	60	58.39	0.216
9.60	4.27	60	58.37	0.216
12.66	6.57	60	58.32	0.216
15.79	7.76	60	58.29	0.216
18.89	8.82	59	58.32	0.216
6.37	2.83	122	113.53	0.216
9.54	5.19	122	113.53	0.216
12.69	7.10	122	113.51	0.216
15.79	8.87	122	113.49	0.216
18.82	11.59	122	113.53	0.216

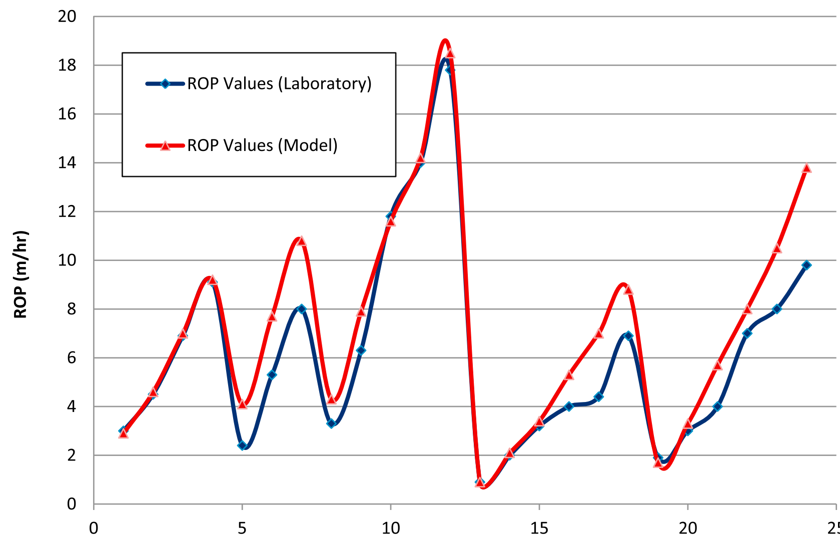

Fig. 13. Comparison between calculated and reported experimental *ROP* values utilizing the developed *ROP* model.

Table 4
Coefficients for permeable and impermeable rock types to use for converting *CCS* to *UCS*.

Coefficients	Permeable rocks	Impermeable rocks
a_s	0.24	0.24
b_s	0.58	0.78

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.

$$CCS = UCS^{*}(1 + a_s^{*} P_e^{\,b_s}) \tag{25}$$

CCS: confined rock compressive strength (MPa), *UCS*: unconfined rock compressive strength (MPa), P_e: confinement pressures (MPa), a_s, b_s: 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.

$$P_e = P_{BHP} - P_p \tag{26}$$

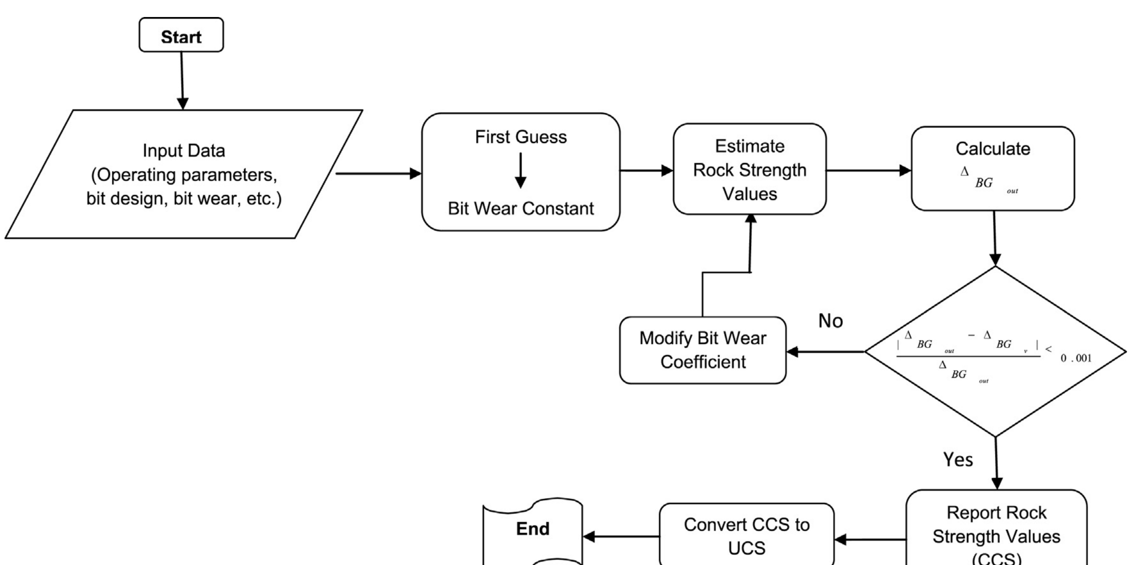

Fig. 14. Flow chart showing steps for estimating rock unconfined compressive strength utilizing new *ROP* model including bit wear effect.

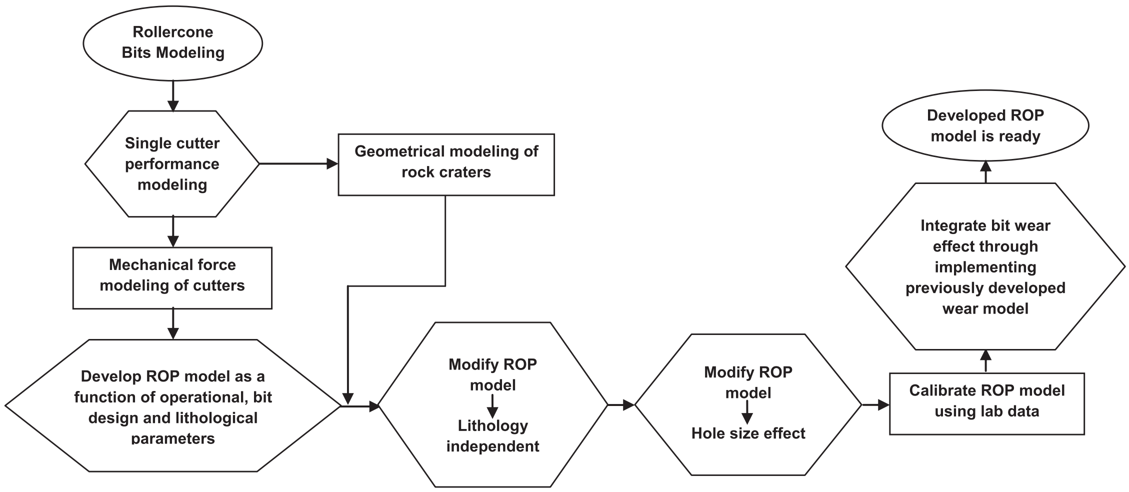

Fig. 15. Flow chart showing the development steps of the newly introduced *ROP* model.

$$P_{Hydrostatic} = 9.8{*}10^{-6}{*}TVD_{*}MW \tag{27}$$

$P_{Hydrostatic}$: hydrostatic pressure (MPa), *TVD*: true vertical depth (m), *MW*: mud weight (kg/m^3).

4. Simulation analysis and technical results

This section illustrates the application of the developed *ROP* model using a newly introduced systematic simulation method. The verification of the model is also discussed utilizing sets of field data from wells drilled in Alberta, Canada, provided by Nexen Energy ULC. and British Gas.

4.1. Generation of rock strength logs utilizing the new ROP model

Having known operational and bit design parameters, rock confined compressive strength (*CCS*) can be back calculated using the newly developed *ROP* model for rollercone bits. The results are useful in generating a reference rock strength database using available offset data for future planning and drilling optimization analysis.

Bit wear effect is also integrated into the *ROP* model utilizing a previously developed wear model (Rampersad et al., 1994) as explained below:

$$W_f = 1 - \left(\frac{\Delta BG}{8}\right) \tag{28}$$

$$\Delta BG = C_c \sum_{i=1}^{n} WOB_{i*}RPM_{i*}A_{r_i*}CCS_i \tag{29}$$

ΔBG: cumulative bit wear function, A_r: formation abrasiveness coefficient, *CCS*: rock confined compressive strength (MPa), W_f: bit wear function, *RPM*: rotary speed of the bit (revolution/min), *WOB*: weight on the bit (T), C_c: bit wear coefficient.

Therefore, the *ROP* model including wear function can be shown as

$$ROP = K{*}\frac{m{*}n_t{*}WOB^{a}{*}RPM^{b}}{CCS^{c}{*}\tan\theta^{d}}{*}f_B(D_B)_{*}W_f \tag{30}$$

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_c).
- 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 ΔBG 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 (ΔBG_v), matches the reported bit wear out as shown below:

$$\frac{|\Delta BG_{out} - \Delta BG_v|}{\Delta BG_{out}} < 0.001 \tag{31}$$

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

$$C_{a_{New}} = C_a. \frac{|\Delta BG_{out} - \Delta BG_{in}|}{|\Delta BG_v - \Delta BG_{in}|} \tag{32}$$

- 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 representaiton 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.

$$UCS = \frac{K_1(1-\phi_N{}^{0.18})_* f}{(\Delta t - 130)^{K_2}} \tag{33}$$

$$f = \frac{(1-\phi_{N-ss}{}^{0.18})}{(1-\phi_{N-sh}{}^{0.18})} \tag{34}$$

$\O_N$: neutron porosity (fraction), $\O_{N\text{-}ss}$: neutron porosity of pure sandstone formation (fraction), $\O_{N\text{-}sh}$: neutron porosity of pure shale formation (fraction), Δt: sonic travel time (μs/m), K_1, K_2: 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.

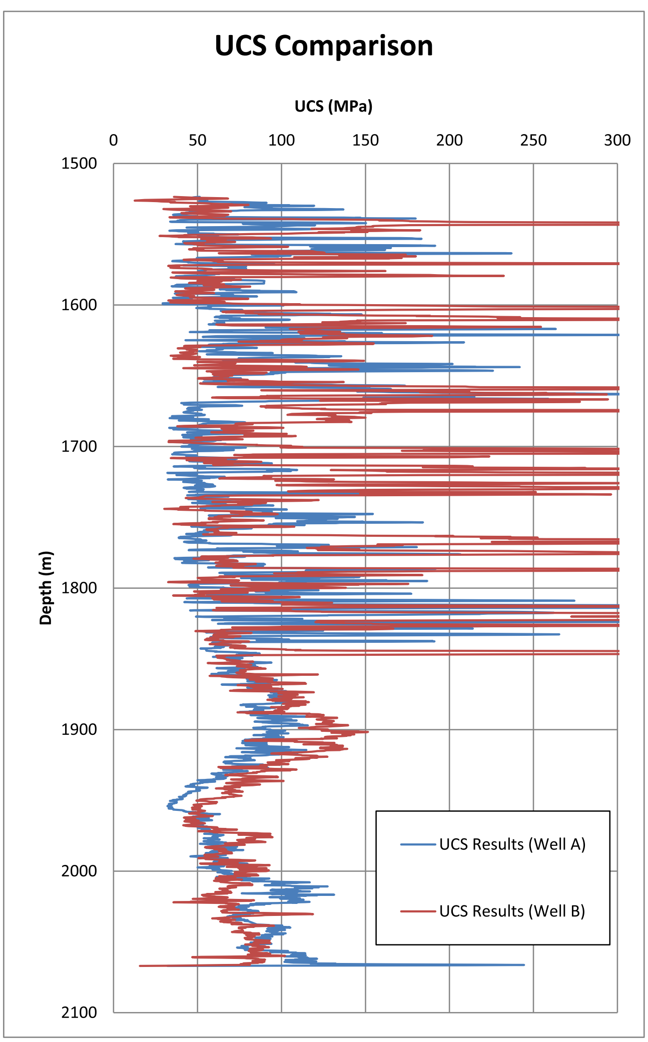

Fig. 16. Comparison between calculated *UCS* values utilizing new *ROP* model for two bit run sections of wells A and B (RMSE: ~75 MPa).

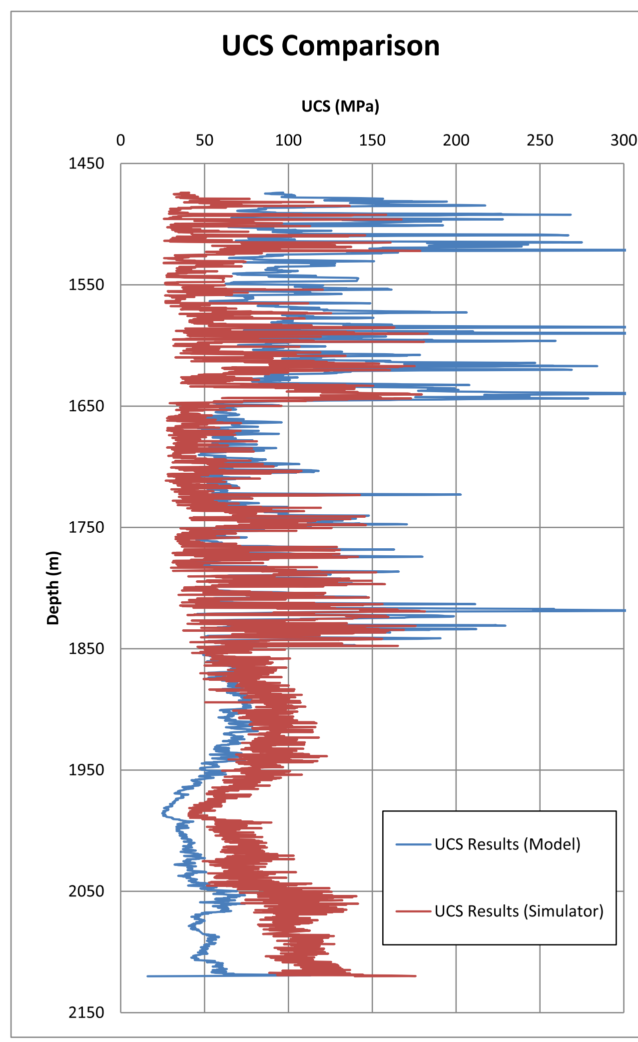

Fig. 17. Comparison between calculated *UCS* values using the *ROP* model and outputs of the drilling simulator for a bit run section of well A (RMSE: ~50 MPa).

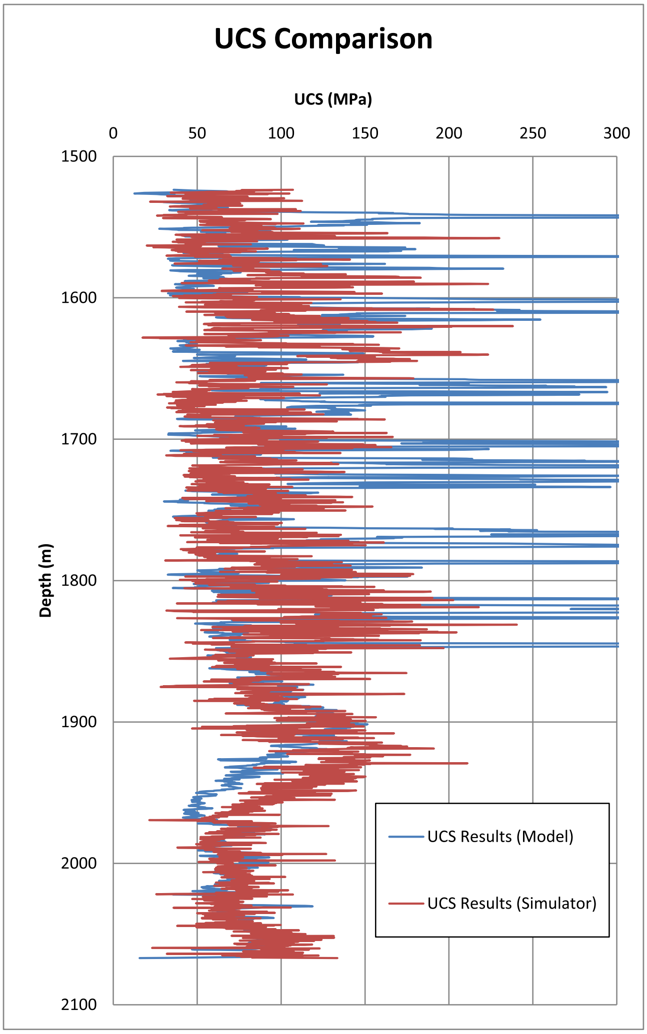

Fig. 18. Comparison between calculated *UCS* values using new *ROP* model and outputs of the drilling simulator for a bit run section of well B (RMSE: ~70 MPa).

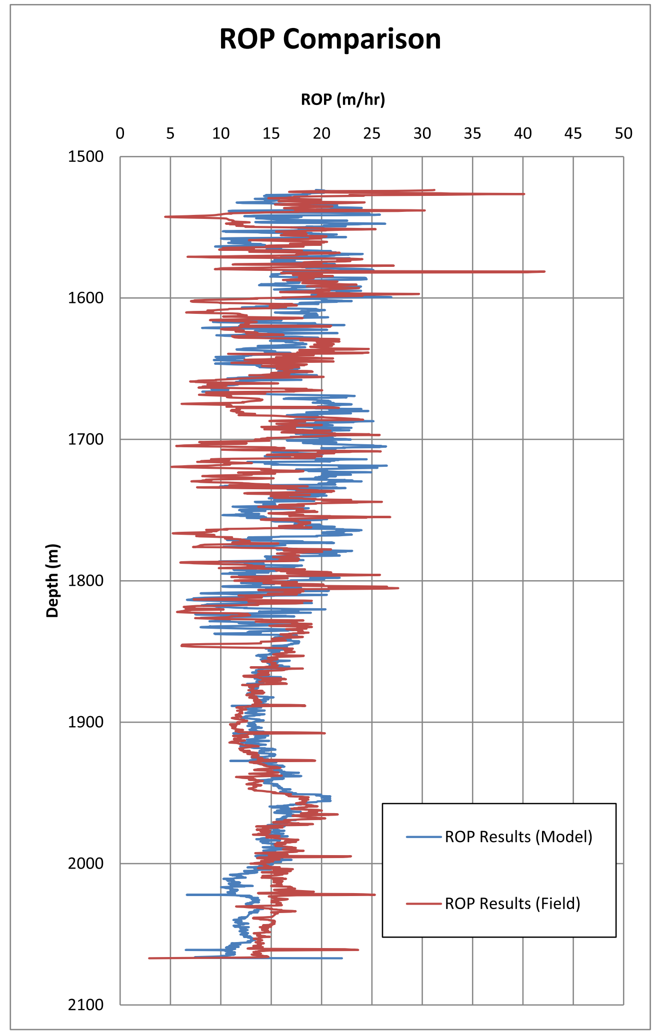

Fig. 19. Comparison between calculated *ROP* values for well B utilizing generated rock strength values of well A using new *ROP* model with reported field *ROP* values (RMSE: ~10 MPa).

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 (θ) 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.
- In this study, a systematic simulation method using the developed *ROP* model is introduced, verified and tested utilizing field data. This simulation method can be employed to recommend optimum drilling operational parameters and bit types for the upcoming wells in the same area wherein offset well data are available.
- 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.

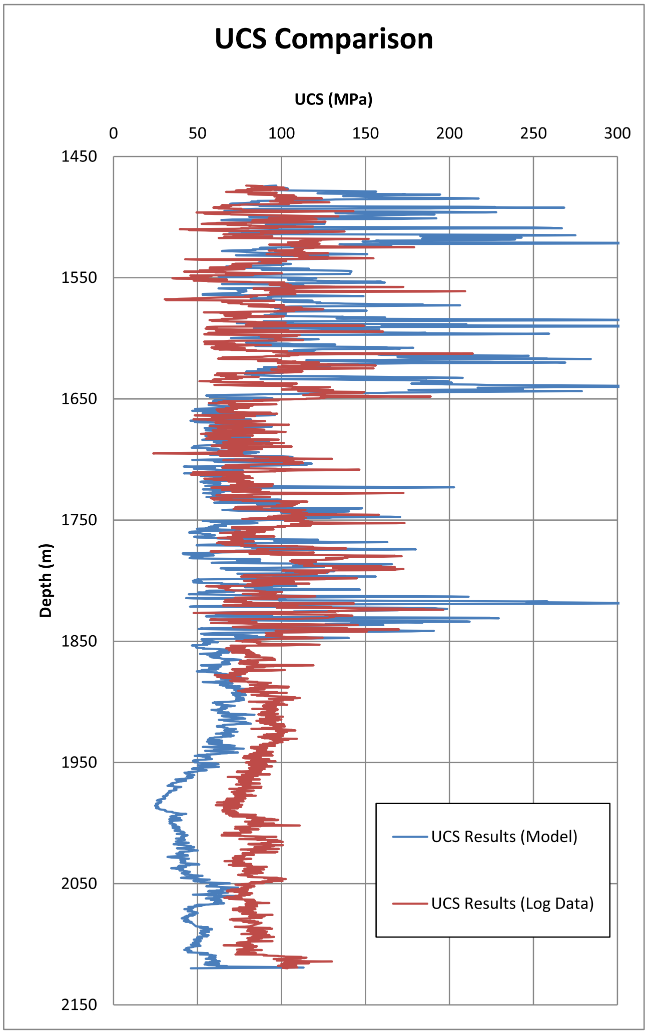

Fig. 20. Comparison between calculated *UCS* values using new *ROP* model and generated rock strength values utilizing log data for a bit run section of well A (RMSE: ~45 MPa)

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