APPENDIX C

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A New Drilling Rate Model for Tricone Bits and Its Application to Predict Rock Compressive Strength

Hareland, G., Wu, A. and Rashidi, B.
University of Calgary, Calgary, Alberta, Canada
James, J. A.
Husky Energy, Calgary, Alberta, Canada

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ABSTRACT: Drilling penetration rate or rate of penetration (ROP) is one of the bit performance indexes. This paper introduces the experimental set-ups for rock failure by inserts of roller cone bits, experiments involved and a method for processing the experimental data. A new drilling ROP model is developed and presented with verification using several groups of lab data. The model is derived directly based on rock craters fractured by a single insert. The work behavior of each insert is not a simple indentation, but includes both crushing and shearing, which represents the actual movement of inserts on a roller cone bit. Finally, the paper focuses on applications of the model in predicting ROP and rock compressive strength with offset well data from Western Canada. The model can reflect the interaction between rock bit and the rock on the bottom hole, and the field verification results are good. The ROP trends from the model match those from the field wells analyzed. In addition, simulations were carried out to predict the unconfined rock strength of formations with the same model using two sets of offset well data. The predicted rock strength matches the strength from log data well, both in trend and values.

1. INTRODUCTION

One way of improving the drilling operation efficiency and to reduce drilling cost is to develop simulation and real time analysis tools. These tools can optimize the drilling operation by predicting and comparing drilling performance. Modeling bit performance is a scientific approach to optimizing drilling performance. Drilling penetration rate or rate of penetration (ROP) is one of the most important bit performance indexes. Therefore improvements in ROP will bring increased efficiency to the drilling industry. Several ROP models for roller cone bits have been developed. These models can select best weight on bit and rotary speed to achieve the minimum cost per foot. Among them, the most complete mathematical drilling models being used includes Bourgoyne and Young's model [1], Warren's model [2, 3], and Warren's model modified by Hareland [4, 5]. These models can be applied in ROP prediction and real-time drilling simulation. However, there are in some cases differences between the between the model predictions and the field observed data. This is often due the technical complexity of the bit-rock interaction, especially in uncontrollable field conditions. In the late 1990s, Ma developed a computer simulation program on the bit-rock interaction [6, 7]. The program reflects the effect of cutting structure on the ROP very well. The drawback of the simulation program is that it is complex and time consuming to run, so it is impossible to use in real-time drilling simulation. This paper shows the development of a simple ROP model to predict the roller cone bit's performance which can be used for real-time simulation purposes. The ROP model is initially built based on experimental data and the results of running a more complex simulation program and lab data. Then the model is modified considering bit wear. The model is a ROP model, and the initial bits simulated are some of the most utilized roller cone insert bits including the IADC 437, 447, 517 and 627 types. The ROP trends from the model match those from field wells. In addition, simulations were carried out to predict the unconfined rock strength of formations with the same model using two sets of offset well data.

The time spent in actually drilling on bottom time is usually a significant portion of total well cost. This means that the correct bit selection and ROP prediction has considerable significance for drilling cost reduction. The ROP model developed in this paper is a stepping stone towards getting a better tool to better achieve lower drilling costs.

2. EXPERIMENTAL METHOD

2.1. Experimental Set-up

When a roller cone bit works, its inserts contact with the rock directly. Therefore indentation tests of single inserts and rock failure tests of single row of inserts are very important to model the performance of a roller cone bit. The rock failure tests by single row of inserts are conducted on a compound rock fracturing machine (Fig. 1). The geometrical structure of the single row of inserts is that same as one row on a roller cone bit, and its movement on the machine can reflect the true movement of inserts of a bit.

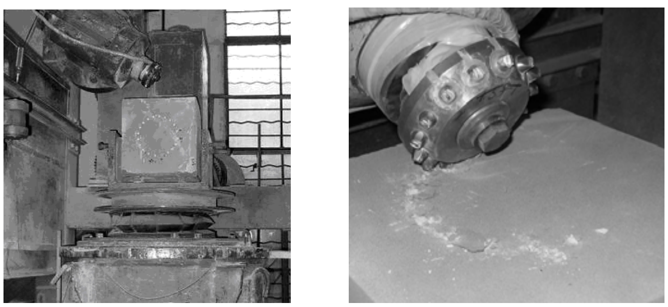


Fig. 1. Experimental set-up for rock fracture tests.

2.2. Experiments

Different single row specimens are designed, and different types of rock samples are selected for the experiments. Fig. 1 shows a rock fracturing test by a single row of insert being conducted. The experiments are done with many combinations of operating parameters (WOB, RPM and cone/cutter geometries)

2.3. Data processing

A dedicated 3-D Scanning and Surveying System is used to measure the projected area, volume and maximum depth of each crater (as shown in Fig. 2).

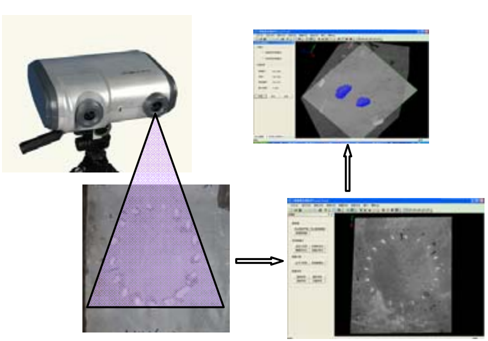


Fig. 2. Measuring and processing of experiment data.

3. DRILL BIT MODELING

As mentioned above, when we model the interaction between the bit and rock, the indentation model of a single tooth is the entry for ROP modeling. The force *F* creating the penetration depth *h* can be a linear combination of the force acting against the tooth flat and the force on the sloping side [8].

$$F = (C_1 w + C_2 h) l \sigma_p \qquad (1)$$

Eq. (1) is setup based on a chisel type tooth; it is suitable for milled tooth bits. However for insert bits, many inserts are not completely chisel shaped, for example conical insert, scoop, and ovoid. It is assumed that there is a relationship as in (Eq. (2)) between the force *F* and the penetration depth *h*.

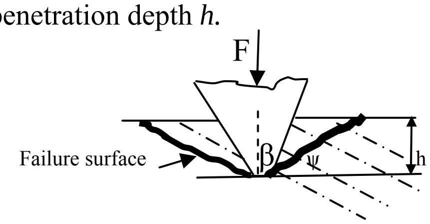


Fig. 3. Rock failure by a wedge.

$$F = a_0 s h^{a_1} \sigma_p^{a_2} \qquad (2)$$

Where

σ_p= ultimate strength of rock at a differential pressure p, psi,

$$\sigma_p = \sigma_0 (1 + a_s p^{b_s}) = \sigma_0 (1 + 0.3 p^{0.7}) \qquad (3)$$

σ_0=unconfined compressive strength

p=differential pressure

β=semi-included angle of a wedge-shaped insert

a0, a1, a2= coefficients

a_s, b_s=coefficients [9]

s=cross area at h

If WOB is applied to the bit, generally there are several inserts which contact with bottom rock and the resultant reactive force is equal to WOB (Eq. (4)).

$$WOB = n_t F = n_t a_0 h^{a_1} \sigma_p^{a_2} \qquad (4)$$

From the above, the average penetration depth can be obtained.

Assuming the crater is conical shape, and then the volume by single tooth is Eq. (5):

$$V = \frac{1}{3} \pi r^2 h = \frac{1}{3} \pi (h \tan(\frac{\pi}{2} - \psi))^2 h \qquad (5)$$

If we know the contact times of each tooth, then the total volume within a revolution can be obtained. Actually, the craters are not cone shape when all contact inserts interact with bottom rock. The RPM is not a linear effect on ROP. Therefore we add a variable to them respectively, so the ROP is expressed as Eq. (6):

$$ROP = K \frac{80 n_t \cdot m \cdot RPM^a}{D_b^2 \tan^2 \psi} \left(\frac{WOB}{100 n_t \sigma_p} \right)^b \qquad (6)$$

Where

D_b= bit diameter

m= number of insert penetrations per revolution

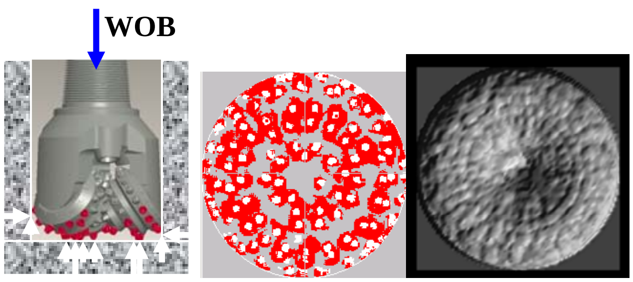
n_t= number of insert in contact with the rock at the bottom

ψ= chip formation angle

a, b= coefficients

K= comprehensive coefficient

m and n_t are related to many factors, such as WOB, bit type, RPM, rock and others, Eq. (7) and (8). They can be obtained roughly by the use of a simulation program for roller cone bits [7]. The program can simulate the working behavior of the cutting structure according to load equilibrium. So instantaneous loads on each insert and cone, craters, and bottom hole pattern can also be obtained (as shown in Fig.4). The shortcoming of this type of program is that it is very time-consuming. The need for a new faster and more user friendly ROP model was identified and is presented in this paper. The coefficient a, b can be obtained from experimental data.



a b c

Fig. 4. Simulation of roller cone bit and rock interaction (a: Contact teeth and load equilibrium; b: Craters by inserts; c: 3D bottom hole pattern).

$$m = f(WOB, RPM, Bit\ type, Rock, ...) \qquad (7)$$

$$n_t = f(WOB, RPM, Bit\ type, Rock, ...) \qquad (8)$$

If a tooth wear function W_f is taken into account [9], the final ROP model becomes Eq. (9):

$$ROP = K \frac{80 n_t \cdot m \cdot RPM^a}{D_b^2 \tan^2 \psi} \left(\frac{WOB}{100 n_t \sigma_p} \right)^b \cdot W_f \qquad (9)$$

Where

$$W_f = 1 - \left(\frac{\Delta BG}{8} \right)^c \qquad (10)$$

ΔBG=tooth dull grade (0-8),

c=coefficients

4. ACQUIRING COEFFICIENTS

According to a part of experiment data and computer simulation technology of roller cone bits, the coefficients in Eq. (9) are obtained (Table 1). Then Eq. (9) can be used to predict ROP of a roller cone bit when compressive strength and other parameters are known. However in most cases the rock strength is unknown, so it needs another relationship between rock strength and some parameters in Eq. (9). For example a relationship between failure angle and rock strength was needed. The rock strength is assumed as a definite value, and the corresponding ROP can be calculated using Eq. (9). The ROPs of some Western Canada wells are calculated with this method and compared with field data (Fig5-11). Table 2 shows the field data.

Table 1. Coefficients for different combinations

	437		537		637	
	Shale	Lime	Shale	Lime	Shale	Lime
K	0.025	0.917	0.257	0.195	0.503	0.010
a	0.645	0.633	0.606	0.546	0.267	0.549
b	0.888	1.410	1.197	1.197	1.169	0.936

Table 2. Field data from Western Canada wells

Case	IADC Code	Size (mm)	Depth out(m)	Hours	Dull Grade
1	437	222	1169	51.5	6
2	447	222	2477	59.75	1
3	437	222	1104	49.5	E
4	437	311	670	42.25	3
5	517	222	1020	50.25	6
6	627	222	1626	72.75	E

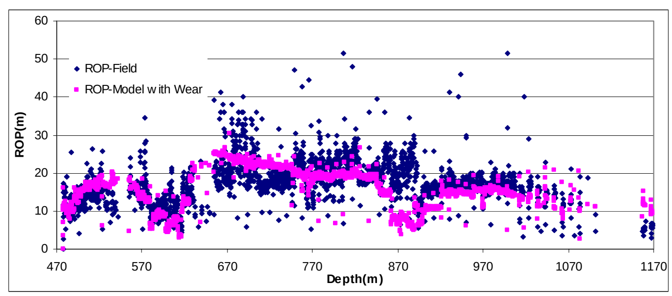


Figure 5: ROP Comparison of field and model with wear (IADC437, BIVOUAC Field)

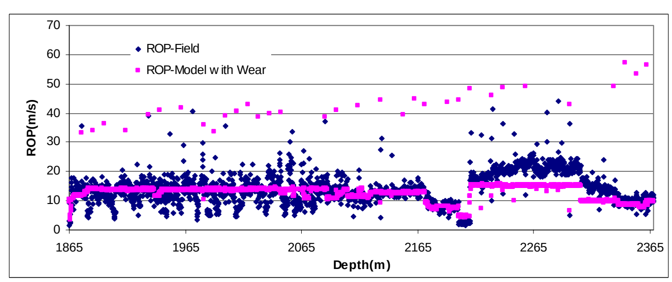


Figure 6: ROP Comparison of field and model without wear (IADC447, COLUMBIA Field)

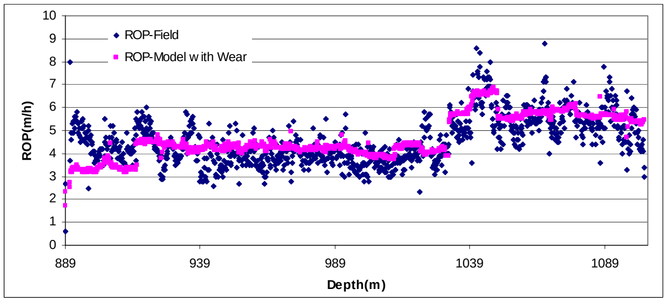


Figure 7: ROP Comparison of field and model with wear (IADC437, BLACK Field)

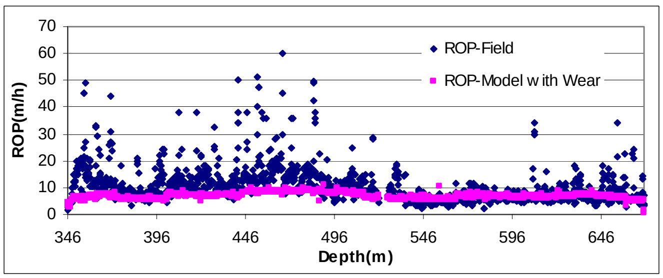


Figure 8: ROP Comparison of field and model with wear (IADC437, KAKWA Field)

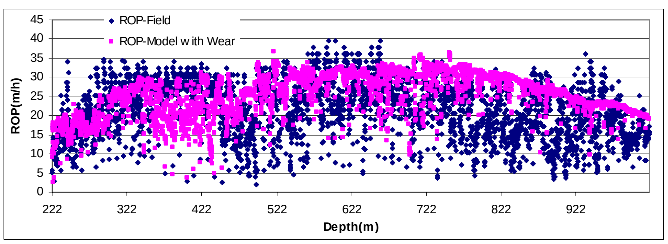


Figure 9: ROP Comparison of field and model with wear (IADC517, WAPITI Field)

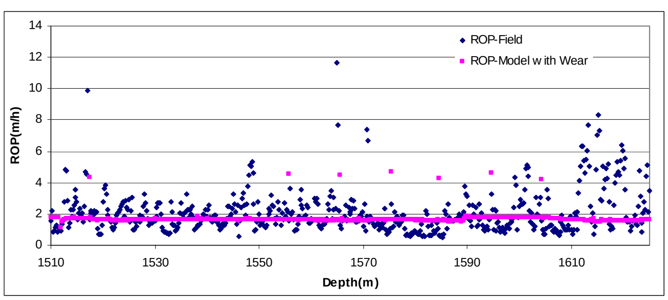


Figure 10: ROP Comparison of field and model with wear (IADC627, BUBBLES Field)

5. PREDICTION OF ROCK STRENGTH

In order to make best use of the ROP model, we can invert Eq. (9) and get the compressive strength σ if all other parameters are known. Here we choose a set of data from offset wells (Ansell and Sundance) to predict both ROP and rock strength.

First, calculated the compressive strength of rock in section 1524-2067 of Sundance well, and then made use of the strength to predict the ROP in section 1474-2120 in the same formations in the nearby Ansell well. The compressive strength of rock in section 1474-2120 of Ansell well was also calculated using sonic log data [10]. The comparison of ROP and strength are as shown in Fig11-12.

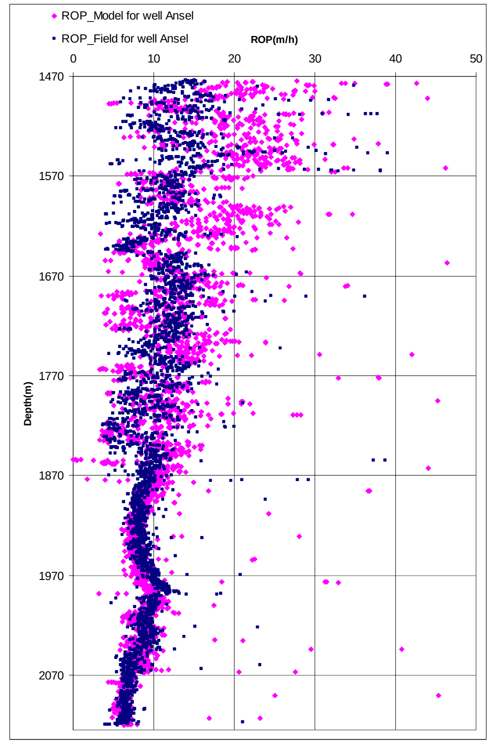


Figure 11: ROP Comparison of field and model with wear (well Ansell)

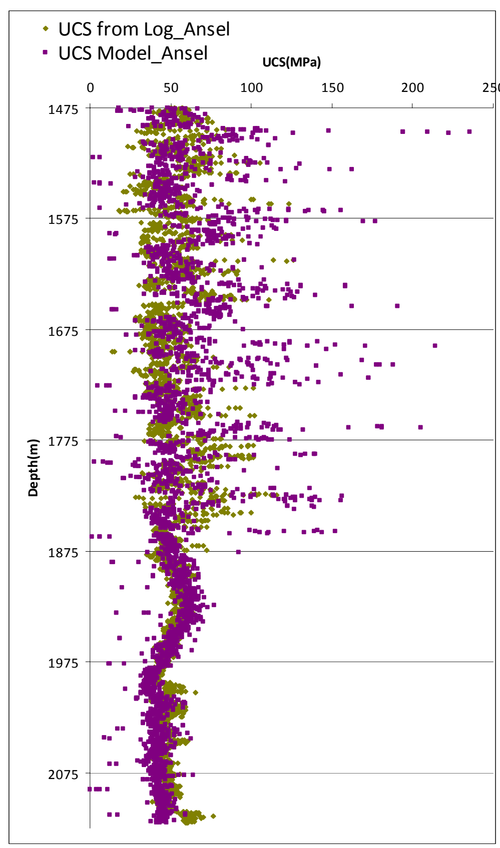


Figure 12: UCS Comparison of field and model with wear (well Ansell)

6. CONCLUSIONS

From Fig. 5-11, we can see the application results are a good match. From Fig. 12, the predicted rock strength matches the strength from log data well, both in trend and values. Based on these observations it is stipulated that the model can be used to predict not only ROP of a roller cone bit, but also the unconfined compressive strength of the formation drilled.

The model in this paper is different from others in that the model can reflect the practical working action of a roller cone bit when fracturing rock on the bottom hole during the drilling operation. It will be applied in the real-time drilling simulation software in the near future, which will play an important role in Western Canada well drilling. In addition, this paper provides a new method of studying rock failure mechanism by inserts of roller cone bits.

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