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A Drilling Rate Model for Roller Cone Bits and Its Application

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Abstract

Modeling bit performance is a scientific approach to optimizing drilling performance. Drilling rate or rate of penetration (ROP) is one of bit performance indexes. Several ROP models for roller cone bits have been developed over the years. However, there exist errors to some extent between these models and the field. This is because of the technical complexity of the bit-rock interaction. This paper introduces a new ROP model based on the interaction mechanism between drill bit and rock. The ROP model takes into account bit structure, especially cutting structure, and drilling parameters, such as WOB, RPM, and bit wear. The paper then focuses on applications of the ROP model in predicting drilling rate and rock compressive strength with drilling well data from Western Canada.

Simulations were carried out using the ROP model for roller cone bits with two sets of offset well drilling data. The predicted ROP and rock strength when the model is used in an inverted mode were compared with field data or results from log rock strength data respectively. The comparison shows the ROP model can predict drilling operational ROP and rock compressive strength well.

The ROP model is different from others in that it takes into account the bit cutting structure in more detail. The model can reflect the effects of different number of inserts and insert shape on ROP.

The model is especially useful when selecting a roller cone bit with same IADC code but with different insert features and designs, and can be used in optimizing the drilling parameters in a planning mode and predicting the unconfined compressive strength in an inverted mode.

Introduction

This work aims to propose a rate of penetration (ROP) model considering bit cutting structure and some drilling parameters. The model is verified for an insert roller cone bit, IADC437, with correlation coefficients determined from laboratory data. Then using the ROP model is verified with a secondary set of laboratory data. The predicted results have a good match with the second set of laboratory data. The ROP model had to be modified some to be used under real field drilling conditions. The model was then used to predict the ROP with different datasets but with the same cutting structure and IADC code (for example 437). It has been observed that the ROP generally increases with increasing WOB and RPM. Therefore these variables may have significant effects on ROP. Ma developed a ROP simulator which can reflect the effects of tiny changes in cutting structure on ROP [1]. The complex simulation model is different from others in that it takes into account the bit cutting structure in more detail, for example, if an insert type or inserts number changes, then the ROP model can reflect this change. Generally an insert cone bit with IADC437 has many types and different cutting elements. Most ROP models typically make ROP calculation based on only the IADC code. Because the Ma simulator is very complicated and time consuming, it was necessary to develop a simple and practical ROP model which can be used in real time drilling simulation to predict bit performance and rock compressive strength. A simple ROP model is developed in this paper based on an indentation mechanism of a single tooth and then integrated across the bit face as in the Ma simulator.

ROP Modeling

When a roller cone bit is working, its teeth interact with the rock of bottom hole. It can be assumed that the teeth on a bit are in shape of wedge or chisel. 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 [2].

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

Where

$$C_1 = \frac{1-\sin\phi}{2\sin\phi}\left[\frac{1+\sin\phi}{1-\sin\phi}\exp(\pi\tan\phi)-1\right]$$

$$C_2 = \frac{1-\sin\phi}{\sin\phi}\left[(\tan\phi+\tan\beta)(1+\sin\phi)\exp(2\Xi\tan\phi)-\tan\beta\right]$$

$$\Xi = \beta + \frac{\pi}{4} + \frac{\phi}{2}$$

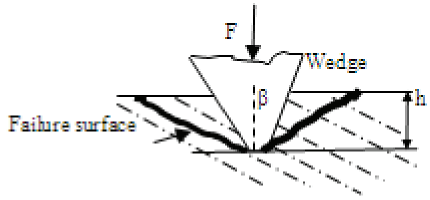


Figure 1 Indentation model of a single wedge

$$\sigma_p = \sigma_0 (1 + a_s p^{b_s})$$ Eq.2

φ = angle of internal friction of rock
σ_p = ultimate strength of rock at a differential pressure p, psi,
a_s, b_s= lithology coefficients [3]
σ_0 =unconfined compressive strength
p =differential pressure
β =semi-included angle of a wedge-shaped insert
h =depth of insert penetration
w = width of insert flat
l = length of insert flat

When WOB is applied to the bit, generally there are several inserts which contact with the bottom rock so that the resultant reactive force is equal to WOB.

$$WOB = n_t F = 100 n_t ((C_1 w + C_2 h) l \sigma_p)$$ Eq.3

Rearranging the average penetration depth is given by:

$$h = \frac{1}{C_2}\left(\frac{WOB}{100 n_t l \sigma_p} - C_1 w\right)$$ Eq.4

Assuming the crater is conical shape then the volume by a single tooth is:

$$V = \frac{1}{3}\pi r^2 h$$
$$= \frac{1}{3}\pi (h\tan(\frac{\pi}{2}-\psi))^2 h$$
$$= \frac{\pi}{3\tan^2\psi}\left(\frac{1}{C_2}\left(\frac{WOB}{100 n_t l \sigma_p} - C_1 w\right)\right)^3$$ Eq.5

Knowing the contact times of each tooth, the total volume within one revolution can be obtained, and the ROP is expressed as:

$$ROP = \frac{\pi}{3\tan^2\psi}\left(\frac{1}{C_2}\left(\frac{WOB}{100 n_t l \sigma_p} - C_1 w\right)\right)^3 \cdot n_t \cdot m \cdot RPM \cdot 60 \cdot \frac{1}{\frac{1}{4}\pi D_b^2}$$
$$= \frac{80 n_t \cdot m \cdot RPM}{D_b^2 \tan^2\psi}\left(\frac{1}{C_2}\left(\frac{WOB}{100 n_t l \sigma_p} - C_1 w\right)\right)^3$$ Eq.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

The generated craters are not all in cone shape when all contact inserts interact with bottom rock. The RPM also doesn't bring linear effect on ROP. Therefore we add a variable to them respectively.

$$ROP = \frac{80n_t \cdot m \cdot RPM^a}{D_b^2 \tan^2 \psi}\left(\frac{1}{C_2}\left(\frac{WOB}{100n_t l\sigma_p} - C_1 w\right)\right)^b \quad \text{Eq.7}$$

m and n_t are related to many factors, such as WOB, bit type, RPM and rock properties and are a function of them. The coefficients *a* and *b* are obtained from experimental data.

$$m = f_1(WOB, RPM, Bit\,type, Rock, ...) \quad \text{Eq.8}$$

$$n_t = f_2(WOB, RPM, Bit\,type, Rock, ...) \quad \text{Eq.9}$$

However, m and n_t can be obtained using the Ma *Simulation Program* for a tricone bit design. ψ is obtained experimentally, or from an empirical formula, or calculated as follows if φ is known [4].

$$\psi = \frac{\frac{\pi}{2} - \beta - \varphi}{2} \quad \text{Eq.10}$$

Given that bit type and formation, *w, l, β,* D_b, *φ*, and *ψ* are know, *m* and n_t can be computed by the Ma complex model simulation program under certain drilling conditions.

If the factors of tooth wear is taken into account, and the final ROP model becomes:

$$ROP = K\frac{80 \cdot n_t \cdot m \cdot RPM^a}{D_b^2 \cdot \tan^2 \psi}\left(\frac{1}{C_2}\left(\frac{WOB}{100 \cdot n_t \cdot l \cdot \sigma_p} - C_1 \cdot w\right)\right)^b \cdot \left(1 - d\left(\frac{DG}{8}\right)^c\right) \quad \text{Eq.11}$$

Where

$$DG = f(WOB, RPM, UCS, ...) \quad \text{Eq.12}$$

DG =tooth dull grade (0-8) and calculated from a tooth wear model.
c =coefficient
d =coefficient
K =comprehensive coefficient

Table 1: Experimental data

WOB(ton)	RPM	Confinement	UCS(MPa)	CCS(MPa)	ROP(m/h)
3.338439	62	2.5988225	37	58.66041	3.346704
6.332149	62	2.5126156	37	58.15491	6.69036
9.525439	62	2.4957948	37	58.05568	8.574024
12.65069	61	2.5126156	37	58.15491	10.84174
15.7714	61	2.4600505	37	57.84413	13.05458
18.86037	61	2.5988225	37	58.66041	13.85011
21.61367	60	2.4684609	37	57.89399	15.9319
3.333903	123	2.5147182	37	58.1673	2.54508
6.395652	123	2.5063078	37	58.11772	7.75716
9.493687	122	2.4978974	37	58.06809	14.20978
12.60533	122	2.5126156	37	58.15491	16.10563
15.65801	121	2.4915896	37	58.03084	19.09877

Sample experimental laboratory data are shown in Table 1 and was used to calibrate the ROP formula for a 437IADC code bit when drilling shale and can be expressed as:

$$ROP = K\frac{80 \cdot n_t \cdot m \cdot RPM^{0.64}}{D_b^2 \cdot \tan^2 \psi}\left(\frac{1}{C_2}\left(\frac{WOB}{100 \cdot n_t \cdot l \cdot \sigma_p} - C_1 \cdot w\right)\right)^{0.89} \cdot \left(1 - d\left(\frac{DG}{8}\right)^c\right) \quad \text{Eq.13}$$

ROP prediction with drilling parameters in the laboratory

The following Figures 2(a)-(h) shows the comparison of values calculated by the model to those from full scale 8.5" 437 IADC experimental laboratory data.

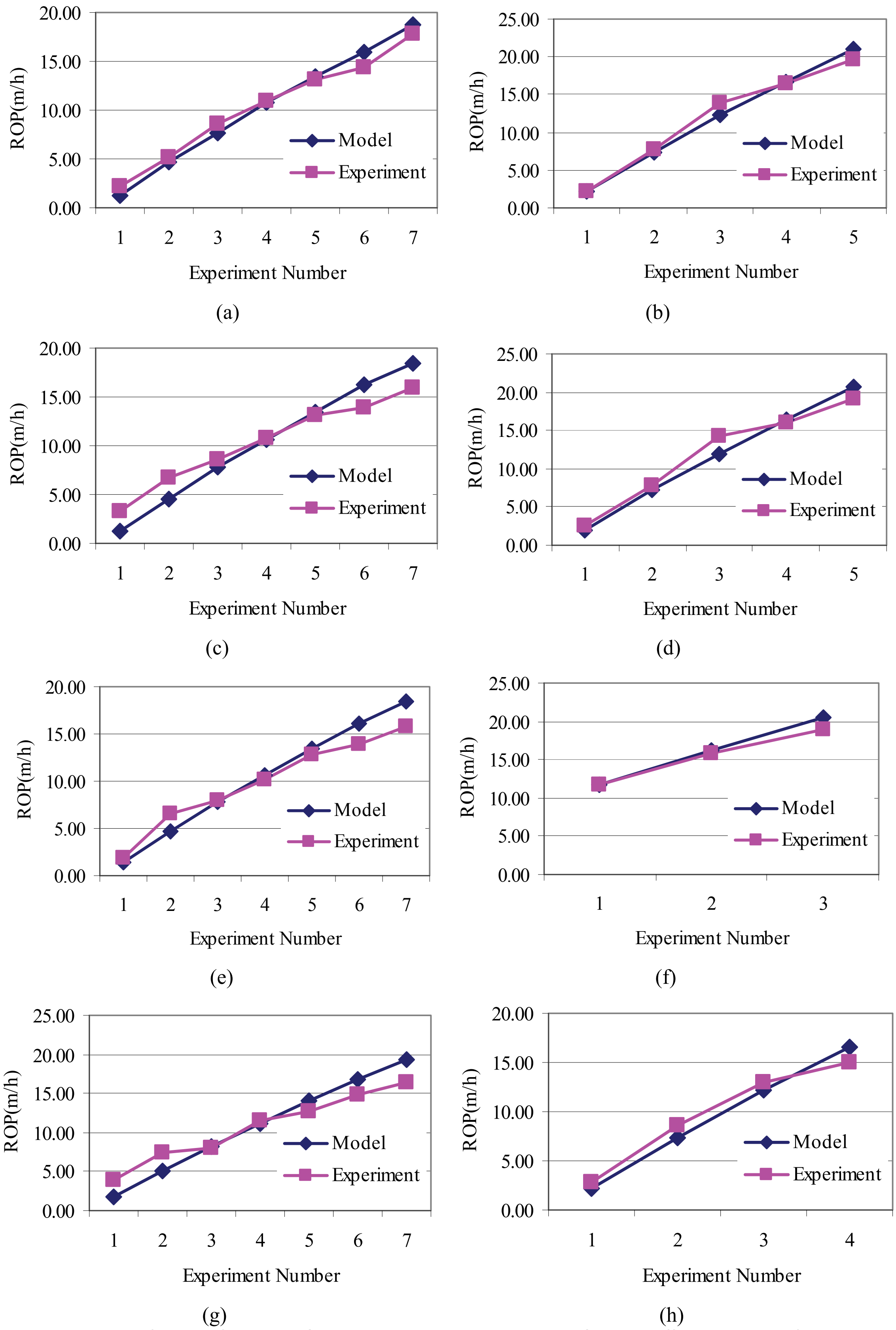


Figure 2. The comparison of results from the ROP model and the experiment (IADC 437, 8 different groups of data: a,b,c,d,e,f,g,h)

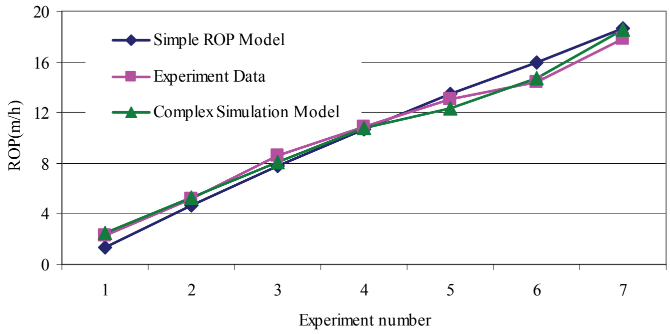
It can be seen that the results from the ROP model is a good match to the lab data. It is obvious that the difference is getting bigger with the increase of WOB; this is because the ROP model at this time does not take hydraulics into account.

Table 2: Comparison of ROP from two models and the experiment (low RPM, Shale)

WOB	RPM	Simple Model	Experiment	Complex Model
3.356583	62	1.304658	2.231	2.523
6.38658	62	4.63123	5.188	5.324
9.489151	62	7.726521	8.608	8.091
12.63708	62	10.71347	10.869	10.772
15.68976	62	13.5133	13.100	12.338
18.82408	60	15.97602	14.380	14.745
21.52296	62	18.67979	17.822	18.507

Table 3: Comparison of ROP from two models and the experiment (high RPM, Shale)

WOB	RPM	Simple Model	Experiment	Complex Model
3.469981	124	2.245173	2.093976	5.258
6.50905	123	7.375409	7.757159	10.57
9.638837	123	12.20291	13.81659	16.067
12.69151	123	16.68736	16.46225	20.925
15.71244	123	20.98113	19.67179	24.477



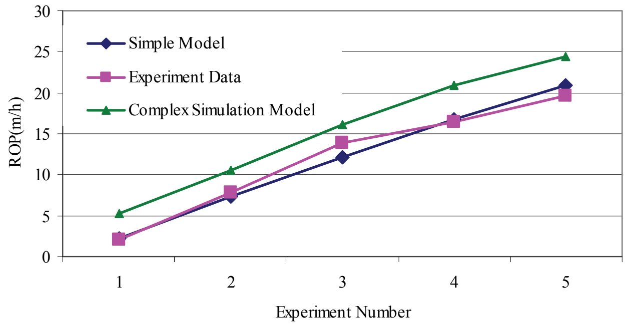


Figure 3. The comparison of data from simple ROP model, experiment, and complex simulation model (left: low RPM, right: high RPM)

From Table 2 and 3 and Figure 3, both the complex model and the simple model can predict ROP well under relative low RPM conditions. However the complex model can not predict ROP well with high RPM situation.

ROP prediction with drilling parameters in the field

What will happen if we apply this model on the field? Figure 4 and Figure 5 show the result comparison between from the model and the field data where the bits had no or little bit wear. *K* for Figure 4 and 5 is from laboratory data. Bit wear out and distribution throughout the run is considered in Figure 6 and 7 and shows a prediction with same IADC code.

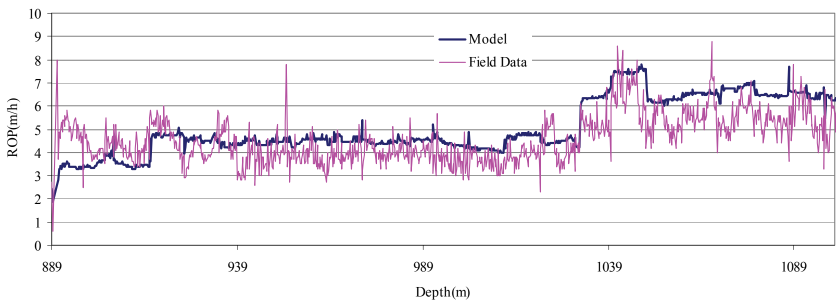


Figure 4. The comparison of ROP from the model and the field (IADC 437)

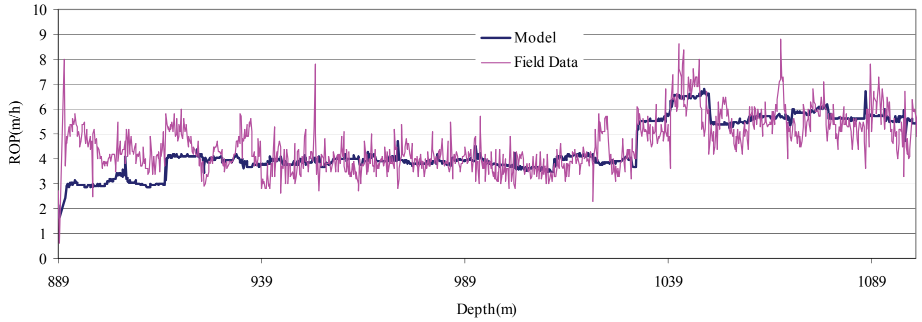


Figure 5. The comparison of ROP from the modified model and the field (IADC 437)

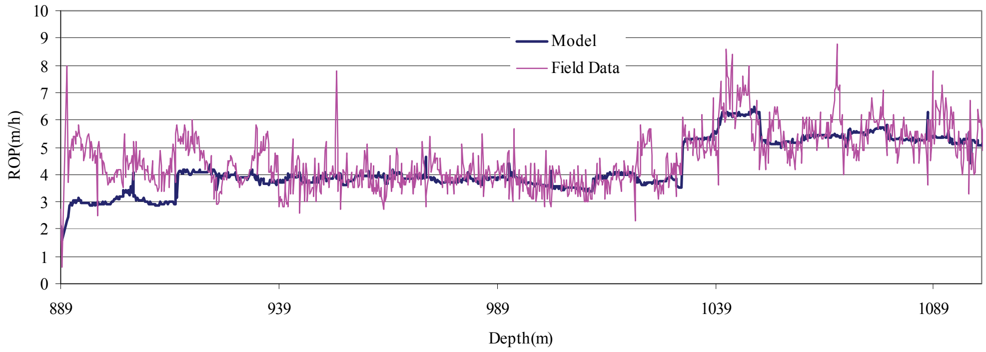


Figure 6. The comparison of ROP from the modified model and field data (IADC 437-Bit Wear=2)

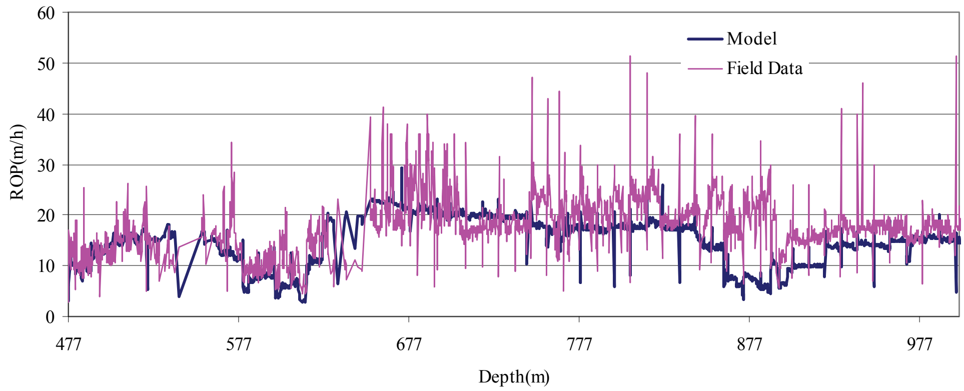


Figure 7. The comparison of ROP from the modified model and field data (IADC 437 – Bit Wear=3)

UCS prediction with drilling parameters in the field

Rearranging the ROP model can get an expression that can be used to predict the rock compressive strength in Eq.14.

$$\sigma_p = WOB \cdot \left(100 \cdot n_t \cdot l \cdot \left(C_2 \left(\frac{ROP \cdot D_b^2 \cdot \tan^2 \psi}{K \cdot 80 \cdot n_t \cdot m \cdot RPM^a \left(1 - \left(\frac{DG}{8} \right)^c \right)} \right)^{\frac{1}{b}} + C_1 \cdot w \right) \right)^{-1} \qquad \text{Eq.14}$$

$$UCS = \sigma_p (1 + a_s p^{b_s})^{-1} \qquad \text{Eq.15}$$

Figure 8 shows the comparison of results from the inverted ROP model compared sonic log rock strength data [5]. It can be seen that the results match well, both trend and values.

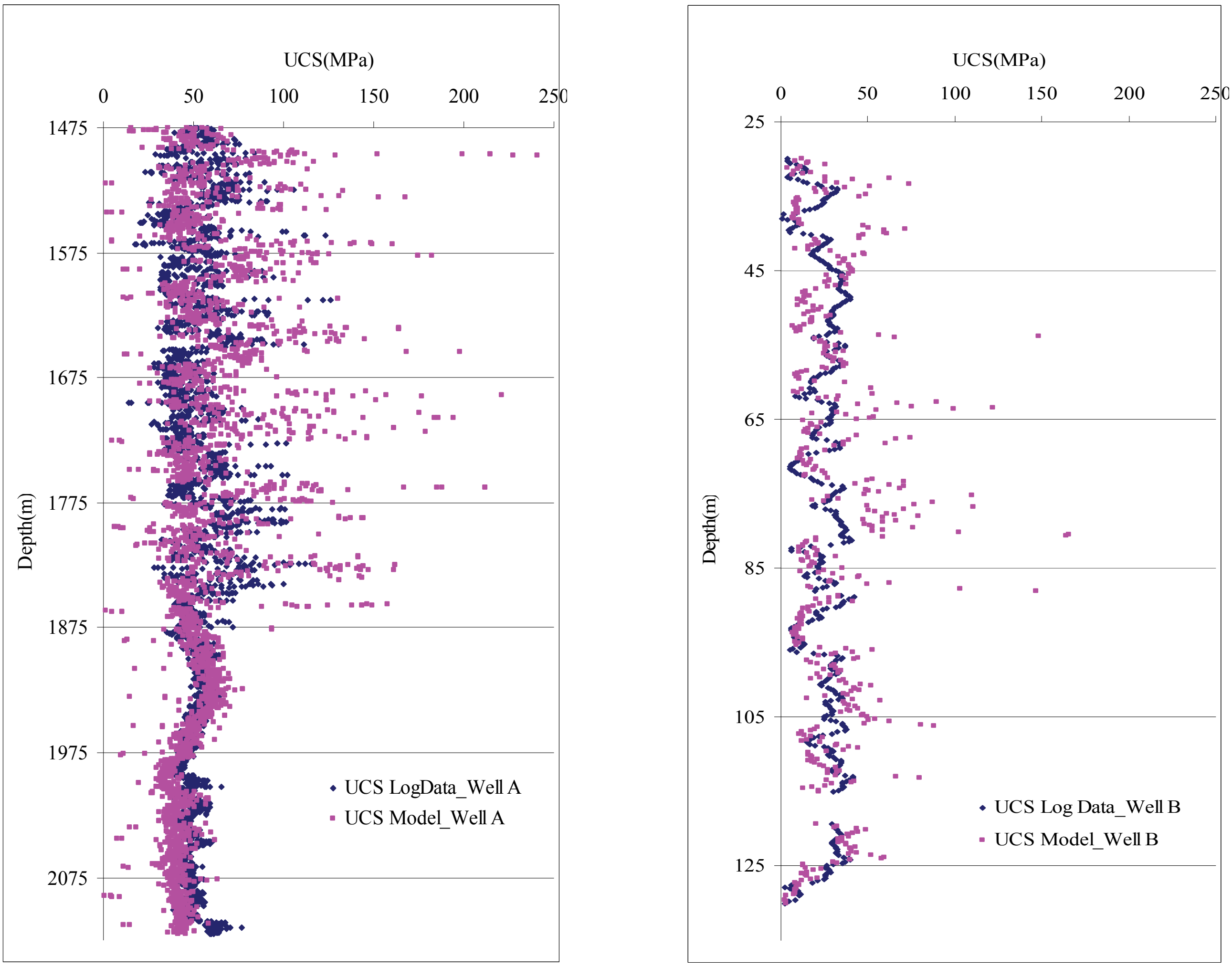


Figure 8. The comparison of UCS from the inverted model and the log data (left: IADC517, right: IADC 117)

Conclusions

The comparison of results from the new rollercone ROP model and lab or field data presented in this paper shows that the model can reflect drilling process of roller cone bits. The ROP model proposed herein can be used to predict both ROP and UCS under most conditions. The complex simulation model developed by Ma doesn't take RPM into account in the rock-breaking mechanism, and it can't be directly applied in predicting ROP in the field operations. The next step in the model development will be to integrate hydraulics into the model and to find a good relationship between failure angle and UCS. It is believed that the model could be used in real time simulation and analysis of oil well drilling when these effects are integrated.

References

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