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ROP Model for PDC Bits in Geothermal Drilling

Akhtarmanesh, S.
Oklahoma State University, Stillwater, OK, USA
Atashnezhad, A., Hareland, G. and Al Dushaishi, M.
Oklahoma State University, Stillwater, OK, USA

ABSTRACT: Geothermal energy is a renewable source of energy, where heat extraction is preferentially balanced with the reservoir's natural heat recharge rate. The objective of this paper is to present and validate a novel rate of penetration (ROP) model for drilling hard and abrasive formations including granite formations for polycrystalline diamond compact (PDC) bits. The ROP model was developed based on a derived relationship of a threshold weight on cutter (WOC) and its corresponding depth of cut (DOC) for a single cutter. Laboratory data was used to scale the derived single cutter relationship to a full-hole ROP model for PDC bits. The ROP model includes a non-linear correlation for Phase I (inefficient drilling due to low WOB values) and a linear Phase II (efficient drilling) ROP response to WOB. The ROP model was verified using measured drilling parameter data from Utah FORGE well# 58-32 and data from Chocolate Mountains well # 17-8 in Southern California. When compared to oil and gas well drilling, geothermal drilling in granitic formations can be more difficult and complicated due to rock hardness and high temperatures. PDC bits can increase ROP and optimize drilling for these types of hard formations. This paper provides novel insight into the ROP response of PDC bits to drilling operational parameters.

1. INTRODUCTION

Geothermal energy is a renewable, reliable, and clean source of energy. Geothermal wells typically need to be drilled into intrusive igneous rocks such as granite. Igneous rocks are formed from the solidification and crystallization of magma in the earth's crust. Granite is a plutonic rock that primarily is made up of quartz, feldspar, and micas.

Oil and gas drilling operations rarely include any interval of an igneous or a metamorphic rock formation, while drilling into these types of rocks is an essential part of the extraction of geothermal energy. PDC bits deliver higher ROPs in soft to medium formations and potentially last longer when compared to roller cone bits. In very hard and abrasive rocks, usually, insert-tooth roller cones are more favorable. However, using PDC bits in these types of rocks has been practiced in many laboratories and field applications. PDC bits that were specially designed for drilling granite and quartzite rocks have been studied by researchers in recent years. Several novel cutting structure enhancements have been proposed and demonstrated in recent years to enhance the penetration response and durability of PDC bits.

Due to the unique challenges related to geothermal drilling, it is imperative to develop a new and accurate model to predict ROP specifically designed for these types of rocks. Several ROP models have been developed for PDC bits for different types of sedimentary rock formations. Hareland and Rampersad (1994) developed a model for drag bits based on the geometry of single-cutter rock interaction, lithology coefficient, and bit wear. They also introduced the concept of equivalent bit radius and dynamic cutter action to scale up the ROP model from a single-cutter to a full bit. Motahhari et al. (2010) developed a new ROP model for PDC bits based on the interactions between a single PDC cutter and rock. Kerkar et al. (2014) developed a new ROP model for PDC bits. They integrated the operational parameters as well as bit details including cutter back rake (BR) and side rake (SR) angles, bit hydraulic function, and bit wear function in the new ROP models. Atashnezhad et al. (2020) introduced a new ROP model for PDC bits in hard rocks and integrated the actual wear flat area and interfacial friction angle (IFA) concepts in their ROP model.

Although significant advancements have been made by the above-mentioned researchers and others in developing ROP models for PDC bits, it is crucial to develop a specifically designed model that is more accurate in predicting ROP values for geothermal drilling applications. The main source of inaccuracy in ROP prediction in these formations is related to the complexity of the drilling mechanisms related to the interaction between a PDC bit and an igneous rock at different operational conditions.

2. TECHNICAL APPROACH

An application-specific ROP model for geothermal drilling can be developed by identifying the preferred regions or phases of drilling. The technical approach comprises developing a predictive relationship for the transition to the efficient drilling region. Empirical correlations are developed for the penetration rate response in the preferred drilling region based upon laboratory drilling data in granitic samples. The model predictions are validated by demonstrating their application to an independent laboratory drilling data set. Additional empirically-derived parameters incorporating bit wear functions are developed for a field drilling data set and used to develop model predictions that are validated by comparison to an independent field data set.

2.1 Theory

Drilling efficiency is a function of several variables and only a few of them (such as WOB and RPM) can be changed by a drilling operator. For different types of drilling bits, three phases of drilling efficiency can be observed related to ROP response to the change of WOB. As shown in Figure 1, Phase I is representative of inefficient drilling due to insufficient WOB. At lower WOB values, low values of depth of cut are expected that cause a higher amount of friction. This is true because the cutting mechanisms in Phase I are limited to the scraping mechanism. The lower WOBs along with higher friction result in lower ROPs, indicating an inefficient drilling process.

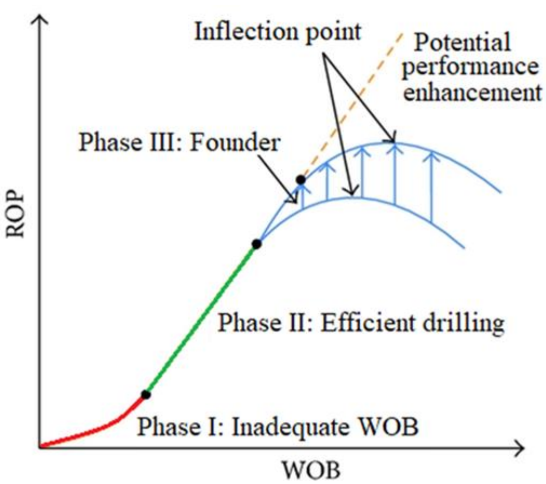

Fig. 1. ROP vs. WOB (Three identifiable phases of drilling)

Phase II is representative of efficient drilling where there is a linear relation between WOB and ROP. Due to the higher WOB values, several cutting mechanisms including chipping, crushing, and scraping are involved that reduces the work done by friction and result in higher ROP values. The optimal range is exceeded when cuttings removal under the PDC bit is less than perfect. This situation is expected for higher values of ROP where a large volume of rock is drilled in a short period of time. In Phase III, drilling fluid cannot effectively remove all drilling cuttings before they get re-drilled under the bit. The founder point is the point that by increasing WOB, the relationship between WOB and ROP deviates from a linear response due to the lack of efficient bit hydraulics resulting in insufficient bottom hole cleaning. One of the objectives of this study is to develop an approach that enables the identification of the transition between Phase I and Phase II to enable operation within the Phase II region of efficient drilling.

2.2 Laboratory data

Drilling tests on Sierra White Granite (SWG) using two new PDC bits were conducted at Sandia National Laboratories (SNL) in the Hard Rock Drilling Facility (HRDF). The collected data includes ROP data at rotational speeds of 80, 120, and 160 RPMs, with incremental weight on bit (WOB) up to 5100 lbs. The diameter of the 4-bladed and 5-bladed PDC bits was 3 3/4" and they were provided by National Oil Varco (NOV). The collected data were used to develop the subject ROP model. Figure 2 shows the face view of the four and five-bladed PDC bits.

Fig. 2. Left: 4-bladed NOV bit, Right: 5-bladed NOV bit

The test results show the existence of different phases of drilling efficiency based on the operational parameters including WOB and RPM. This data was used to derive empirical parameters governing the penetration rate response in the phase of drilling.

Experimental data were also collected from previous experiments conducted by Sandia in the HRDF on SWG using two different 4-bladed and 5-bladed PDC bits provided by Ulterra Drilling Technologies. The diameter of the 4-bladed and 5-bladed PDC bits was 3 3/4". These data include the ROP responses at 100 and 150 RPM rotational speed with incremental WOB up to 4200 lbs. The collected data were used for the verification of the ROP model. Figure 3 shows the face view of the four and five-bladed PDC bits.

Fig. 3. left: 4-bladed Ulterra bit, Right: 5-bladed Ulterra bit. Raymond et al., (2015)

2.3 Field data

Field data were used to develop additional empirical parameters for the penetration rate model that accounts for PDC bit cutter wear. The first field data set was used to develop wear functions; this parameterization was validated by application to a second field data set.

Sandia with the collaboration of the US Navy Geothermal Program Office conducted a series of drilling tests using two PDC bits and one roller cone bit at the geophysical test hole 17-8, located at the northwest Chocolate Mountains, California (Raymond et al., 2012). The first PDC bit (Bit #1) was an eight-blade, eight-nozzle, 8 ½ inch diameter PDC bit and it was provided by NOV. The bit drilled from 1345 ft. to 2070 ft. Figure 4 shows the new condition of Bit #1.

Fig. 4. Bit #1, new condition. Raymond et al., (2012)

The second PDC bit (Bit #2) was a seven-blade, seven-nozzle, 8 ½ inch diameter PDC bit and was also provided by NOV. The bit drilled from 2070 ft. to 2643 ft. Figure 5 shows the new condition of Bit #2.

Fig. 5. Bit #2, new condition. Raymond et al., (2012)

Additional field drilling measurements are available from publicly available data for the DOE-sponsored Frontier Observatory for Researching Geothermal Energy (FORGE) site – a proving ground for developing and demonstrating geothermal energy technology. The drilling data for Utah FORGE well 58-32 was retrieved from the DOE Geothermal Data Repository. Two intervals were drilled using a Smith PDC bit Z713 in the Utah FORGE 58-32 well. An image of the PDC bit that was used in drilling two intervals of Utah FORGE well #58-32 is seen in Figure 6.

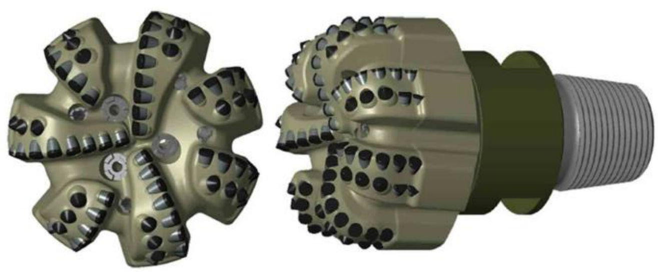

Fig. 6. Image of the 7-bladed PDC bit (Z713) used in Utah FORGE well 58-32

2.4 ROP Model

Based on the experimental data using two NOV (Reed Hycalog, National Oilwell Varco) bits provided by Sandia, it is evident that two distinguished phases exist that are connected at a threshold point. Starting with a single cutter, the threshold weight on a cutter (WOC_t) to produce threshold depth of cut (DOC_t) can be estimated by Eq. (1) and (2) respectively. These threshold values are the transition point between phase I (scraping mechanism) and phase II (including chipping, crushing, and scraping).

$$WOC_t = 270 \times (\frac{RPM}{80})^{0.1} \times \frac{11}{NOC} \times (\frac{Tan(BR)}{Tan(25°)})^{0.2} \times \frac{D_c}{0.51} \times \frac{UCS}{28000} \quad (1)$$

$$DOC_t = 0.018 \times (\frac{80}{RPM})^{0.3} \times \frac{11}{NOC} \times \frac{D_c}{0.51} \quad (2)$$

Where NOC is the number of face cutters of a PDC bit, D_c is cutter diameter in inch. UCS is unconfined compressive strength in psi. BR is the average PDC cutter back rake angle in degrees. The threshold weight on bit (WOB_t) and the threshold rate of penetration (ROP_t) can be calculated based on the threshold weight on a cutter (WOC_t) and threshold depth of cut (DOC_t) by using Eq. (3) and (4) derived in this project. These threshold values are the starting point of effective drilling (phase II) illustrated in figure 1.

$$WOB_t\ (lbf.) = WOC_t(lbf.) \times NOC \quad (3)$$

$$ROP_t\left(\frac{ft}{hr}\right) = DOC_t(in.) \times RPM\left(\frac{rev}{min}\right) \times 5 \quad (4)$$

For phase II, the derived linear full PDC bit model is presented in Eq. (5) and (6). The constants of the model for phase II are based on the drilling data collected for the NOV 4 and 5 bladed PDC bits at RPM values of 80, 120, and 160.

$$ROP = G \times \frac{RPM \times (WOB - WOB_t)}{UCS\left[1 + 0.3(\frac{RPM}{100})\right]} + ROP_t \quad (5)$$

$$G = 880 \times \frac{NOB^{0.3}}{NOC^{1.05}} \times \frac{D_c \times \cos(SR)}{D_b^2 \times (\tan(BR))^{0.2}} \quad (6)$$

Where NOB is the number of bit blades. SR is the average PDC cutter side rake angle in degrees. For phase I, a full PDC bit model is presented in Eq. (7). The constants of the model are based on the drilling data collected from the NOV 4 and 5 bladed PDC bits at RPM values of 80, 120, and 160.

$$ROP = 2 \times 10^{-6} \times G \times \frac{RPM^{0.7} \times WOB^{2.6}}{UCS\left[1 + 0.3(\frac{RPM}{100})\right]} \quad (7)$$

3. RESULTS & DISCUSSION

The model-fitting results based on the results for the NOV 4 and 5 blades PDC bits are presented in Figures 7 through 12.

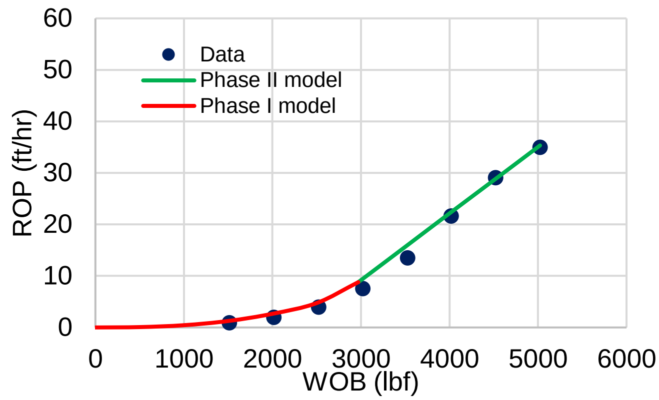

Fig. 7. Comparison between the model estimated ROP and laboratory data for 4-bladed NOV PDC bit at 80 RPM in SWG

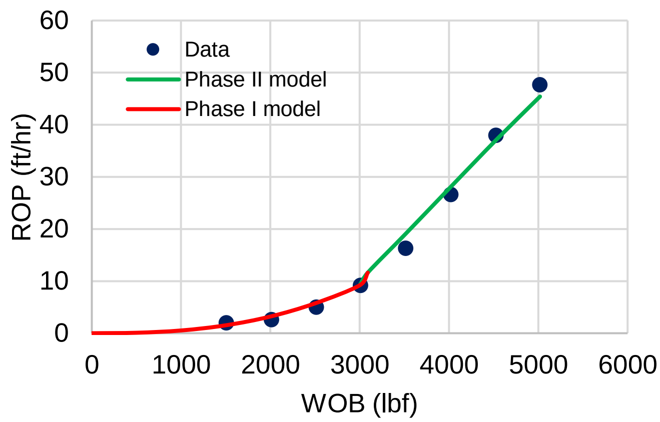

Fig. 8. Comparison between the model estimated ROP and laboratory data for 4-bladed NOV PDC bit at 120 RPM in SWG

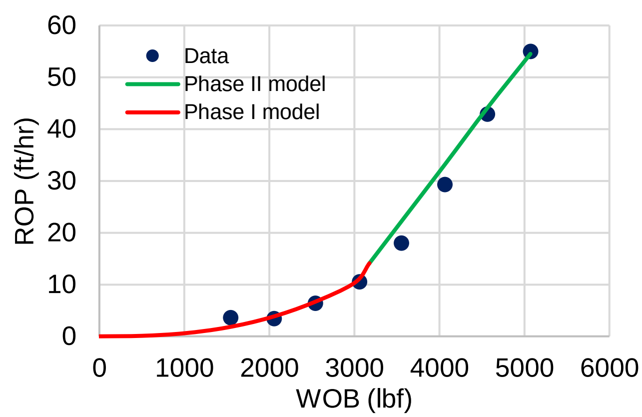

Fig. 9. Comparison between the model estimated ROP and laboratory data for 4-bladed NOV PDC bit at 160 RPM in SWG

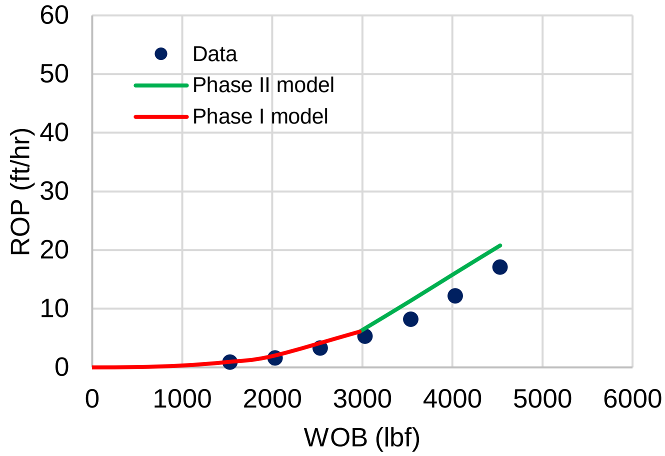

Fig. 10. Comparison between the model estimated ROP and laboratory data for 5-bladed NOV PDC bit at 80 RPM in SWG

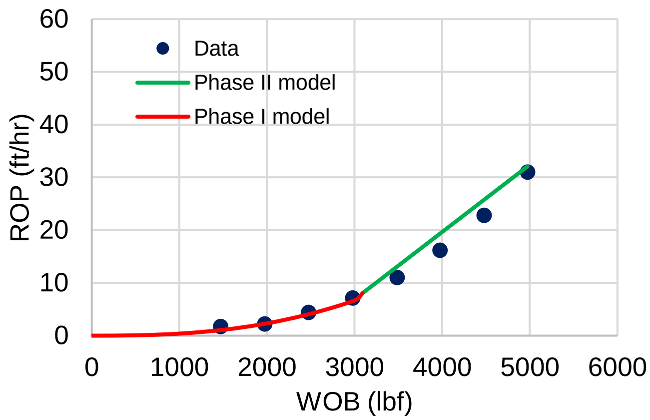

Fig. 11. Comparison between the model estimated ROP and laboratory data for 5-bladed NOV PDC bit at 120 RPM in SWG

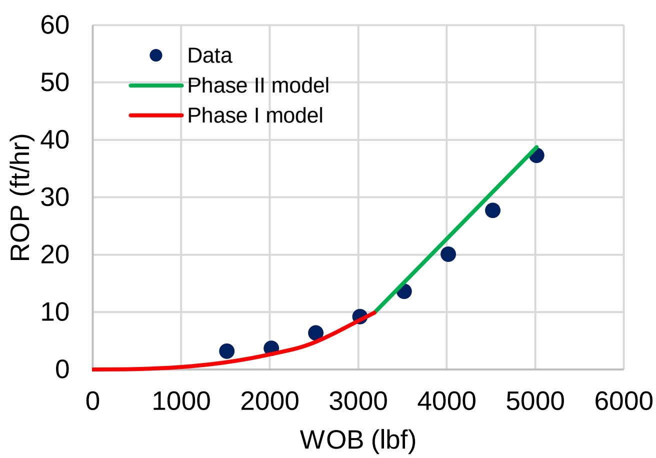

Fig. 12. Comparison between the model estimated ROP and laboratory data for 5-bladed NOV PDC bit at 160 RPM in SWG

To verify the new model, the laboratory drilling datasets (Raymond et al., 2015) were used. The drilling datasets were collected using the Ulterra 4 and 5 bladed PDC bits at RPM values of 100 and 150. The matching results for these sets of data are shown in Figures 13 through 16.

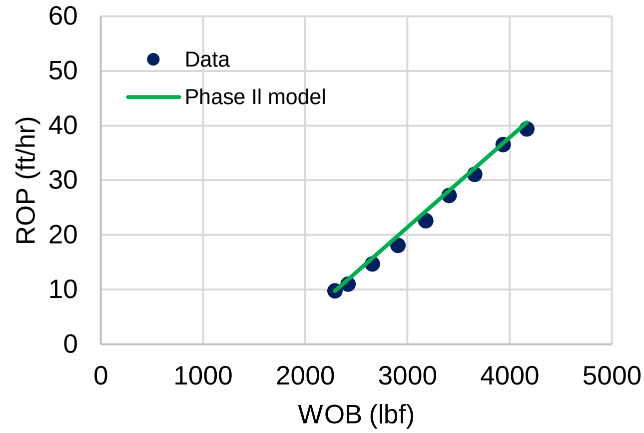

Fig. 13. Comparison between the model estimated ROP and laboratory data for 4 bladed Ulterra PDC bit at 100 RPM in SWG

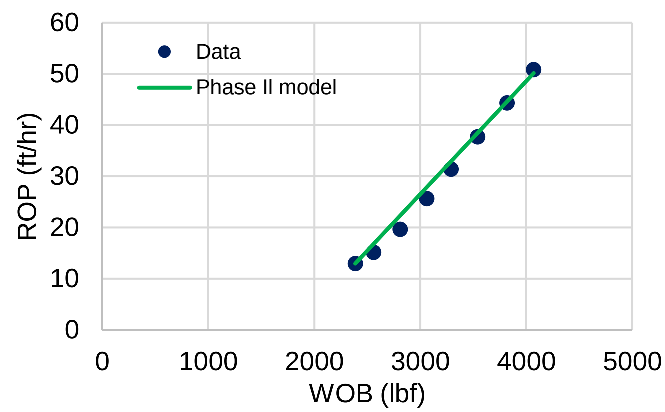

Fig. 14. Comparison between the model estimated ROP and laboratory data for 4 bladed Ulterra PDC bit at 150 RPM in SWG

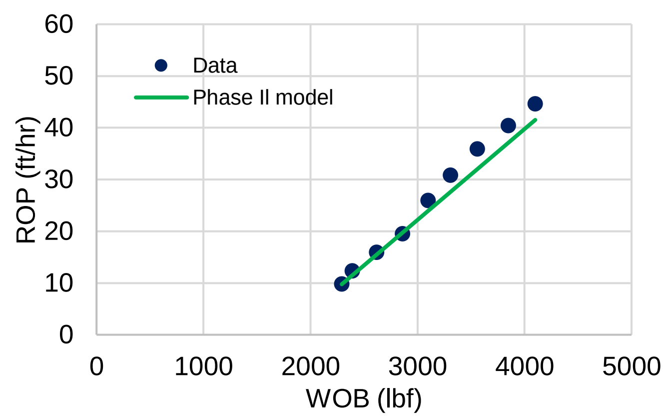

Fig. 15. Comparison between the model estimated ROP and laboratory data for 5 bladed Ulterra PDC bit at 100 RPM in SWG

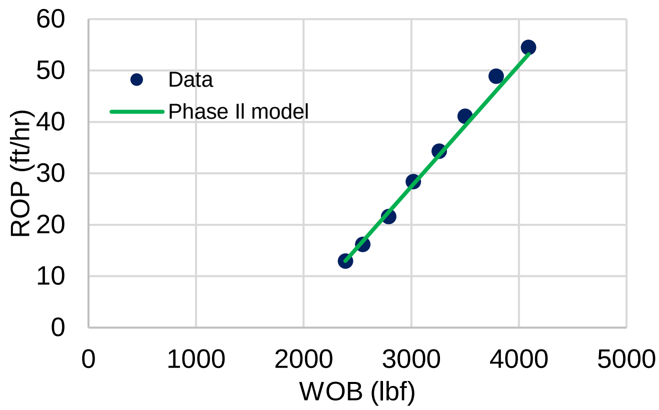

Fig. 16. Comparison between the model estimated ROP and laboratory data for 5 bladed Ulterra PDC bit at 150 RPM in SWG

After ROP model verification for the new Ulterra PDC bits that were tested at Sandia HRDF, it is necessary to include a wear function into the ROP model for field applications. As mentioned above for the drilling data collected from the geophysical test hole 17-8, PDC Bit#1 drilled from 1345 ft. to 2070 ft. the pull out of hole (POH) bit grade (BG) was 2. The PDC Bit#2 drilled from 2070 ft. to 2643 ft. and it's POH BG was equal to 1. Both bits started with BG = 0. (new condition)

A wear function for a full PDC bit, presented by Eq. (8), was developed and used to estimate ROP values for the Chocolate Mountains Bit #1 and Bit #2 by incorporating the wear data (BG) and weight on the cutter.

$$W_f = 1 - (30 \times WOC^{-0.5}) \times \left(\frac{BG}{8}\right)^{0.7} \qquad (8)$$

Figure 17 shows the comparison between the simulated ROP and field ROP for Bit #1 along with their corresponding operational parameters.

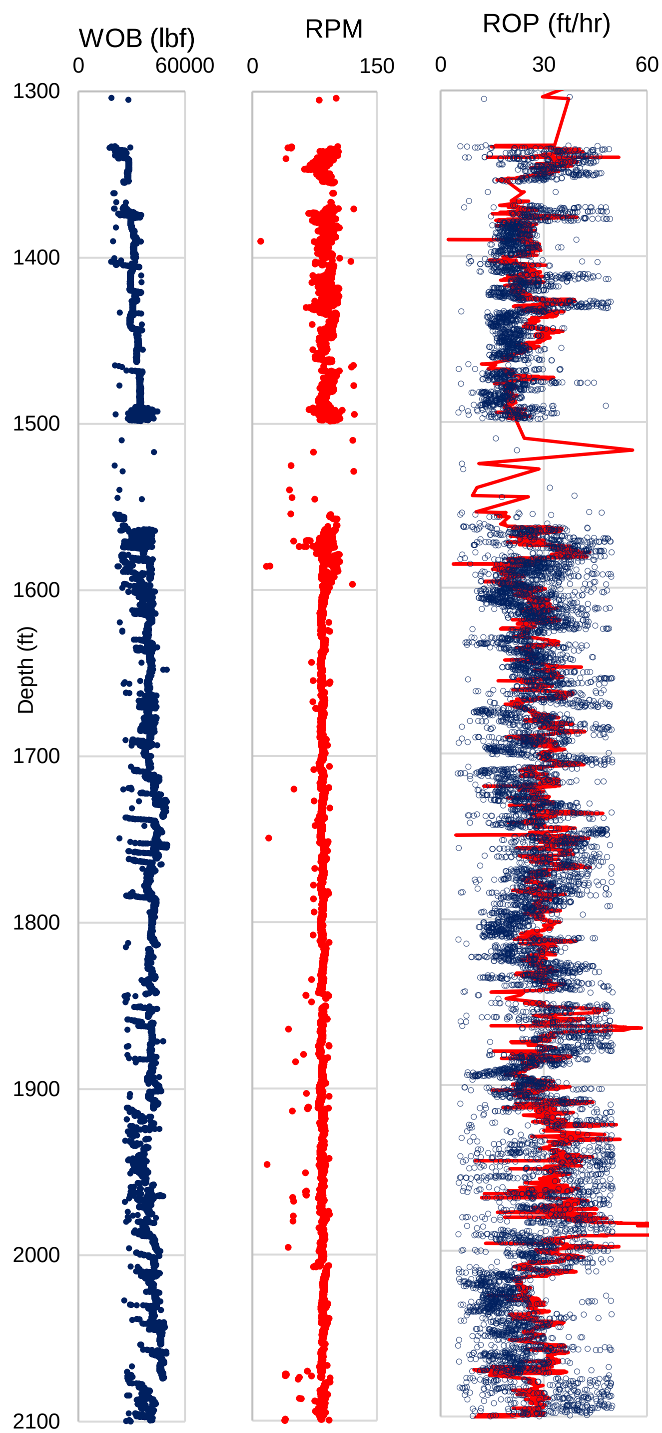

Fig. 17. Comparison between simulated ROP and field ROP for Bit #1 Chocolate Mountains Well 17-8

Figure 18 shows the comparison between the predicted ROP and the field ROP for Bit #2 along with their corresponding operational parameters.

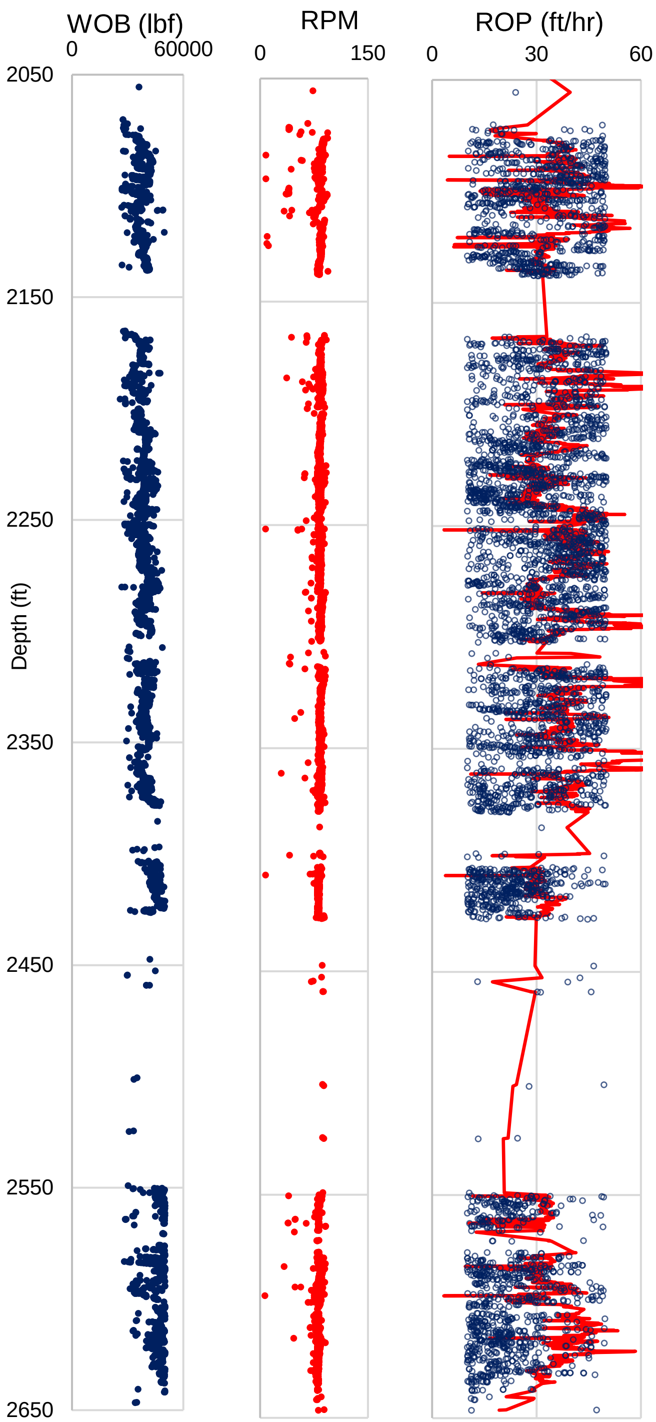

Fig. 18. Comparison between simulated ROP and field ROP for Bit #2 Chocolate Mountains Well 17-8

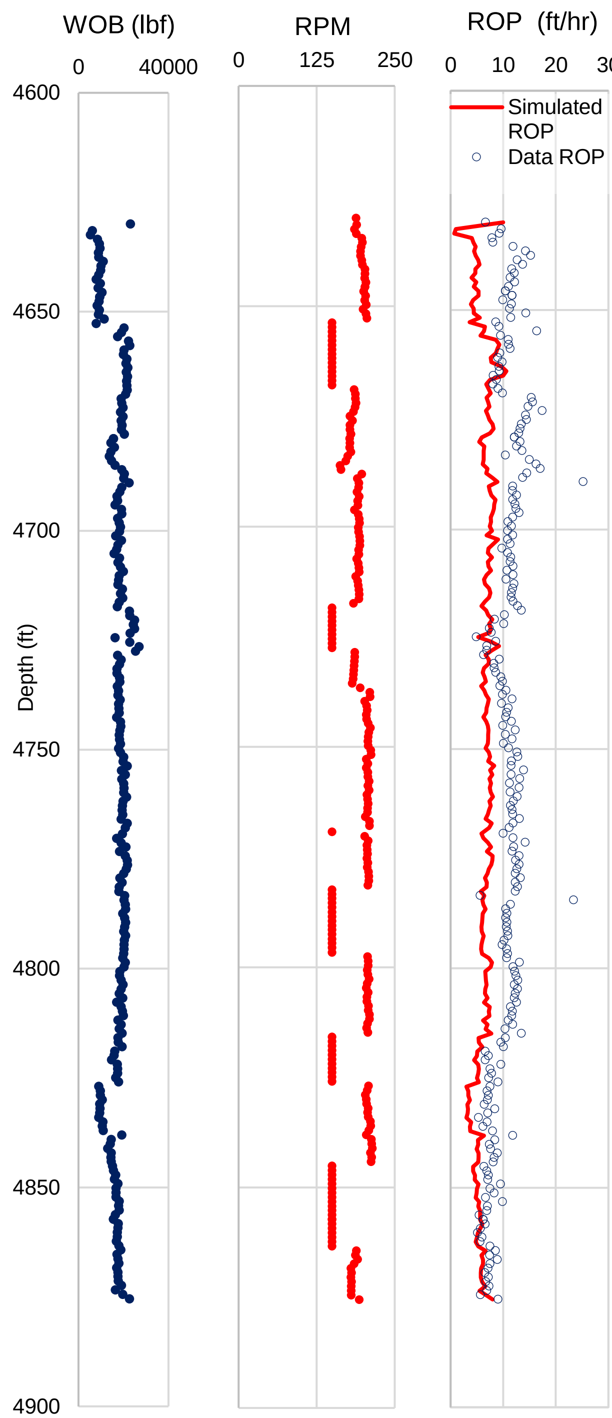

Fig. 19. Comparison between predicted and measured ROP for the upper interval in Utah FORGE Well 58-32

To verify the wear function, ROP values were estimated for two intervals in the Utah FORGE well #58-32 and compared to the ROP data. The run-in hole (RIH) condition for the upper interval was in new condition with a BG equal to zero, and the POH bit grade was 1 (BG = 1). For the lower interval, the RIH bit condition was BG = 1 and POH bit condition was BG = 2.5. The results are presented in Figures 19 and 20.

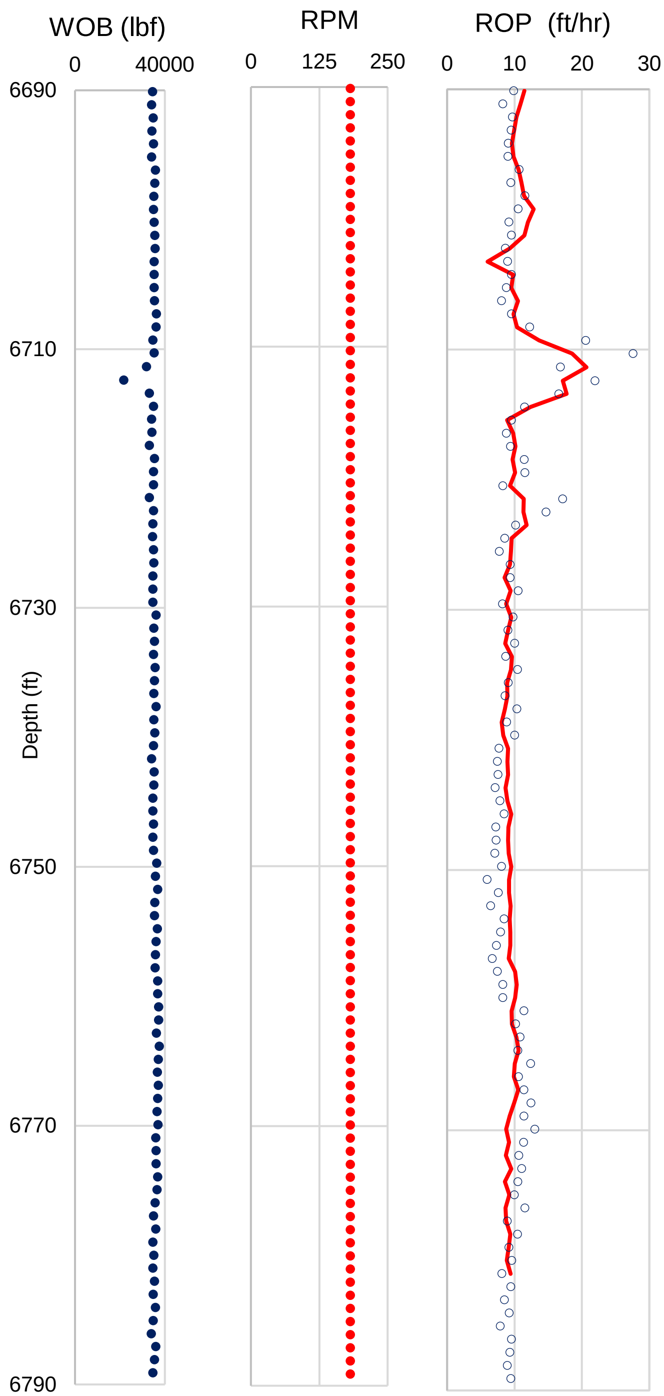

Fig. 20. Comparison between predicted and measured ROP for the lower interval in Utah FORGE Well 58-32

The results indicate that the new ROP model shows promising results when compared to the actual ROP values.

4. CONCLUSION

An ROP model has been developed based on laboratory data from the Sandia Hard Rock Drilling Facility using two new PDC bits provided by NOV. The ROP model was verified with laboratory data on two new PDC bits provided by Ulterra. The ROP model was then improved to include a wear function for the field application, based on the drilling data for two PDC bits with known BGs from the Chocolate Mountains data set. The results were verified using drilling data for two intervals drilled with a PDC bit in Utah FORGE Well 58-32.

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REFERENCES

1. Atashnezhad, A., Akhtarmanesh, S., Sleeper, S., and Hareland, G., 2020. Rate of Penetration (ROP) Model for PDC Drill Bits based on Cutter Rock Interaction. In *54th US Rock Mechanics/Geomechanics Symposium*. American Rock Mechanics Association. 28 June-1 July, Golden, Colorado, USA.
2. Hareland, G., & Rampersad, P. R. 1994. Drag-bit model including wear. In *SPE Latin America/Caribbean Petroleum Engineering Conference*, 21-29 April, Buenos Aires, Argentina. SPE 26957.
3. Kerkar, P. B., Hareland, G., Fonseca, E. R., & Hackbarth, C. J. 2014. Estimation of rock compressive strength using downhole weight-on-bit and drilling models. In *International Petroleum Technology Conference*.
4. Motahhari, H. R., Hareland, G., & James, J. A. 2010. Improved drilling efficiency technique using integrated PDM and PDC bit parameters. In *Journal of Canadian Petroleum Technology*, 49(10), 45-52. SPE-141651-PA.
5. Raymond, D., Buerger, S., Cashion, A., Mesh, M., Radigan, W., and Su, J. 2015. Active Suppression of Drilling System Vibrations for Deep Drilling (SAND2015-9432). Sandia National Laboratories (SNL-NM), Albuquerque, NM.
6. Raymond, D., Knudsen, S., Blankenship, D., Bjornstad, S., Barbour, J., and Schen, A. 2012. PDC Bits Outperform Conventional Bit in Geothermal Drilling Project. In *Geothermal Resources Council Transactions Journal*, v.6, p.307-315.