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Developing a Drilling Optimization System for Improved Overall Rate of Penetration in Geothermal Wells

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ABSTRACT: Geothermal energy is renewable, reliable and environmentally friendly source of energy. The major cost in the development of geothermal wells is the actual drilling of the wells. The main objective of this paper is to introduce a new real-time drilling optimization system designed for granite formation to reduce the overall drilling cost. In this study, a drilling optimization system is verified using drilling data from Utah-Forge well 58-32. The drilling optimization system used the Utah-Forge well 58-32 data to achieve real-time unconfined compressive strength (UCS). Based on the UCS value from the previous feet, the system simulates the ROP for the next drilling feet. The drilling optimization system utilizes the Differential Evolution Algorithm (DEA), which is a metaheuristic method to search the space of solution, to find the best operating parameters (i.e. WOB and RPM) for the next drilling foot. The optimization algorithm takes a maximum cutter temperature into account as a constraint and avoids the accelerated wear. The developed drilling optimization system improves ROP responses and reduces the drilling cost of geothermal wells. The simulated ROP results from the system show a good agreement with the ROP from Utah-Forge well 58-32 drilling data. The drilling time before and after optimization for both intervals were presented.

1. INTRODUCTION

Geothermal energy is a reliable and environmentally friendly source of energy that is constantly accessible without the need for burning fossil fuels or interruption of intermittent availability of wind or solar energies. To access geothermal energy, one or multiple wells have to be drilled into intrusive igneous rock formations such as granite or quartzite that contain a large amount of thermal energy. Drilling operation in extremely hard rocks including granite is rare in the oil and gas industry, while it is an essential part of the extraction of geothermal energy. Due to the unique challenges related to geothermal drilling, it is imperative to keep drilling costs as low as possible by optimizing the drilling process.

The main objective of this paper is to introduce a real-time drilling optimization system design for hard and abrasive formation to reduce the drilling time and the drilling cost of geothermal wells. The drilling optimization system incorporated several modules to optimize the drilling procedure in real-time including a novel PDC ROP model, PDC cutter temperature model (Glowka and Stone, 1985), differential evolution algorithm (DEA), and PDC bit wear model. The drilling optimization system uses the drilling data to simulate the ROP for PDC bit in Utah-Forge well 58-32. Next, the inverse ROP model is used to achieve the real-time UCS for the Utah-Forge well 58-32, which assumes a fixed UCS value for the next foot of drilling. The DEA searches the space of solutions to achieve the optimum WOB and RPM and to maximize the ROP while avoiding the critical cutter temperature. The drilling time of Utah-Forge well 58-32 before and after optimization were compared.

2. RELEVANT WORK

A geological drilling log (GDL) for drilling optimization was developed by Rampersad et al. (1994). They used the inverse ROP model to generate the GDL which later was used for drilling optimization and preplanning.

Rommetveit et al. (2004) developed drilltronics for drilling automation and monitoring. The drilltronics used all surface and subsurface data for drilling optimization and simulation. Dupriest and Koederitz (2005) used mechanical specific energy (MSE) for continuous monitoring and detection of inefficiency in a drilling system. Hareland et al. (2007) used a simulator for drilling optimization in more than 50 wells in western Canada. They achieved an average of 15% to 20% reduction in drilling costs using the simulator results. Eren and Ozbayoglu in 2010 adopted Bourgoyne and Young ROP model (1974) and used multiple regression for drilling optimization. They found that data quality is one of the important parameters for real-time drilling optimization.

Hankins et al. (2015) used the Hareland and Rampersad PDC ROP model (1994) for drilling simulation optimization. They back-calculated the UCS using inverse ROP model for nearby wells which later used for WOB, RPM, hydraulics, and bit specification optimization. Self et al. (2017) used the particle swarm optimization approach for drilling ROP optimization in horizontal wells. They neglected the effect of temperature and drillstring vibration (stick-slip) on drilling performance.

Most programs in the industry use the trial and error method for drilling optimization to find the best operational parameters (Rastegar et al., 2008). This study focused on hard rock drilling in geothermal resources. The main differences between the current study and the previous simulation and optimization works are as follow.

- The drilling optimization system focuses on hard rock drilling in geothermal wells.
- The developed system takes the cutter temperature into account for the design purpose. The cutter temperature has a vital effect on the PDC cutter-wearing phenomena. The new system considers the cutter critical temperature and avoids accelerated wear in PDC bits intelligently.
- The drilling optimization system uses an intelligence search method (DEA) to achieve the best real-time operational parameters (i.e. WOB and RPM).
- The user can choose between different scenarios of optimization including maximizing instantaneous ROP, minimizing instantaneous MSE, or multi-objective optimization approaches (i.e. maximizing ROP/MSE).

In this study, the drilling optimization system accuracy was verified using the data from Utah-Forge well 58-32. The simulated ROPs for two intervals were compared to the corresponding measured ROPs. The drilling optimization system was used to maximize the instantaneous drilling ROP while avoiding thermal accelerated wear. The drilling time for the field data was compared to the optimization results.

3. TECHNICAL APPROACH

The PDC bit used in Utah-Forge drilling is seen in Figure 1. The Z713 is an 8.5-inch diameter, it has 7 blades, 38 cutters with 0.51-inch cutter diameters.

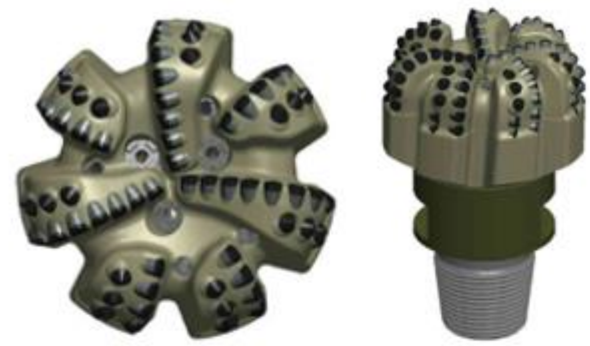

Fig.1 Face and side view of Smith 7 bladed PDC bit (Z713) used in Utah-Forge well 58-32

The drilling data for Utah-Forge well 58-32 were retrieved from the geothermal data repository. The drilling data was fed into the drilling optimization system in a comma-separated values (CSV) format. The input data consist of depth (feet), WOB (lbf), RPM (revolution per minute), confined compressive strength (psi), and ROP (ft/hr). The rock CCS was back-calculated using the sonic log data considering the mud weight and depth. The drilling optimization system benefits from a novel PDC ROP model developed based on lab data for hard rock (Akhtarmanesh et al., 2021).

Two intervals were drilled using Smith PDC bit Z713 in Utah-Forge 58-32 well. The run-in hole (RIH) condition for the first interval (upper) was new (BG=0) and pull out of the hole (POOH) with a bit grade of 1 (BG=1). For the second interval (lower), the RIH bit condition was BG =1 and POOH bit condition was BG=2.5.

4. RESULTS AND DISCUSSION

The simulated ROP using the drilling optimization system is compared with the measured ROP data, along with the operational parameters, for both the upper and lower intervals in Figures 2 through 5.

Oniya et al. (1988) developed a correlation between sound traveling time and rock strength. The sonic log data for both drilling intervals were used to calculate the unconfined compressive rock strength (UCS) using Oniya et al. (1988) correlation, which in this study is referred to as data UCS. The confined compressive strength (CCS), which in this study is referred to as data CCS, was back-calculated, taking the UCS, mud weight (MW), and depth into account.

The CCS data was used to simulate the ROP for both drilling intervals (see Figures 3 and 5). As it is seen in Figures 3 and 5, the simulated ROP from the drilling optimization system is in good agreement with the measured ROP (Data ROP).

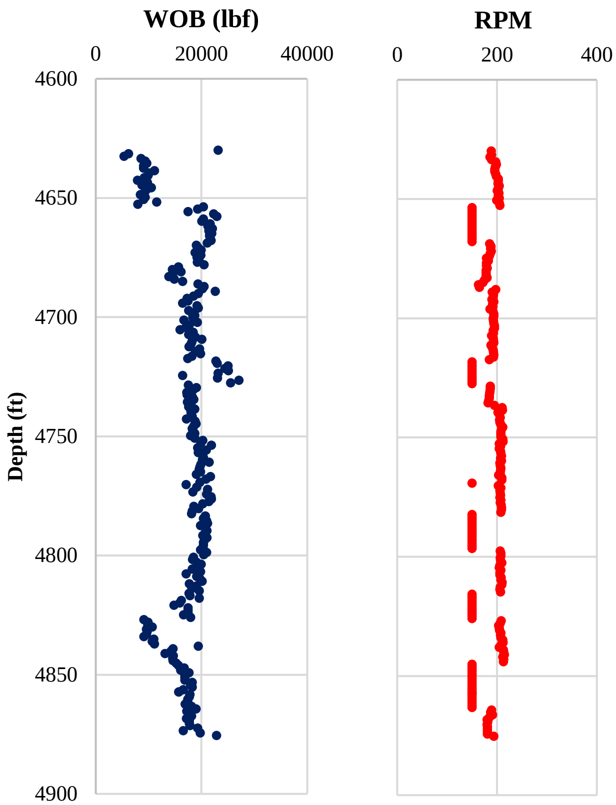

Fig 2. Operational parameters for Utah-Forge well 58-32 upper interval

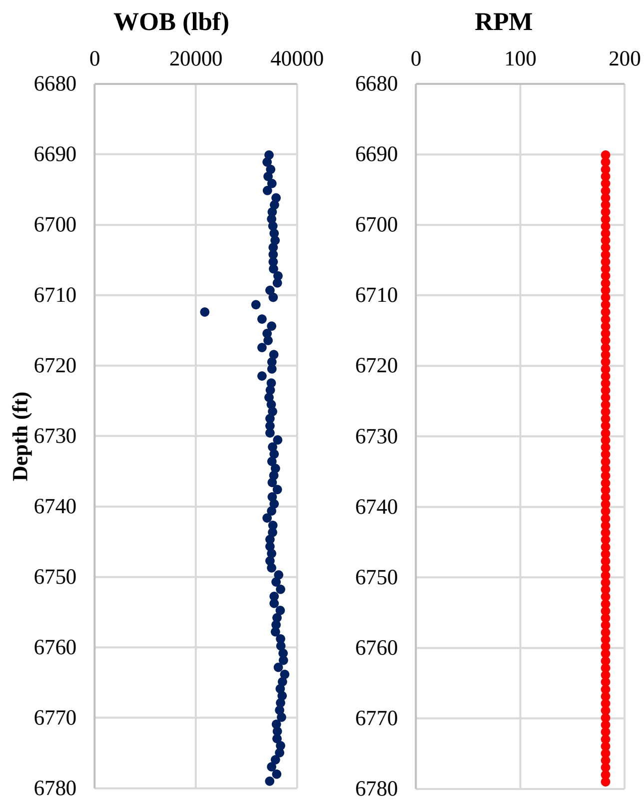

Fig 4. Operational parameters for Utah-Forge well 58-32 lower interval

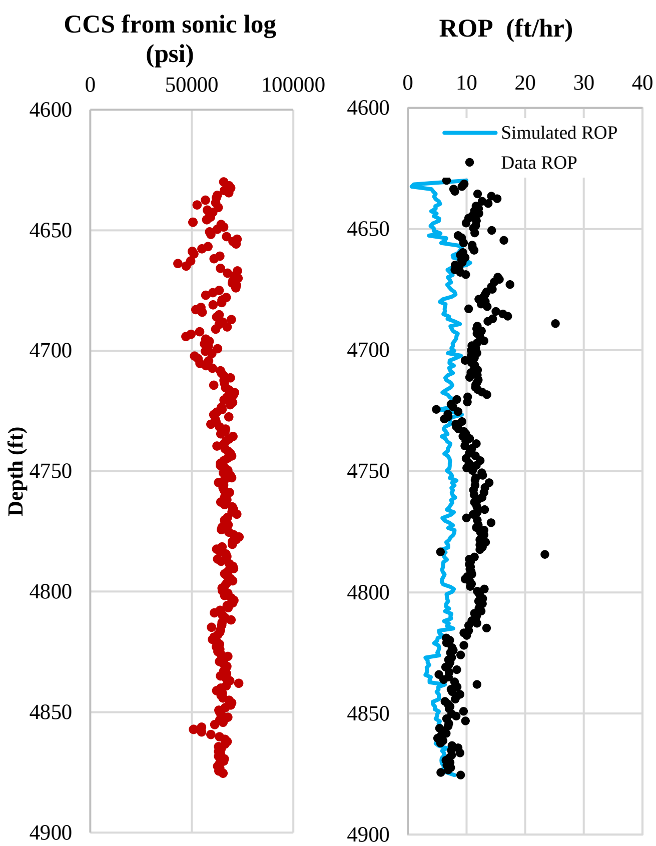

Fig 3. Simulated ROP versus measured ROP for Utah-Forge well 58-32 upper interval

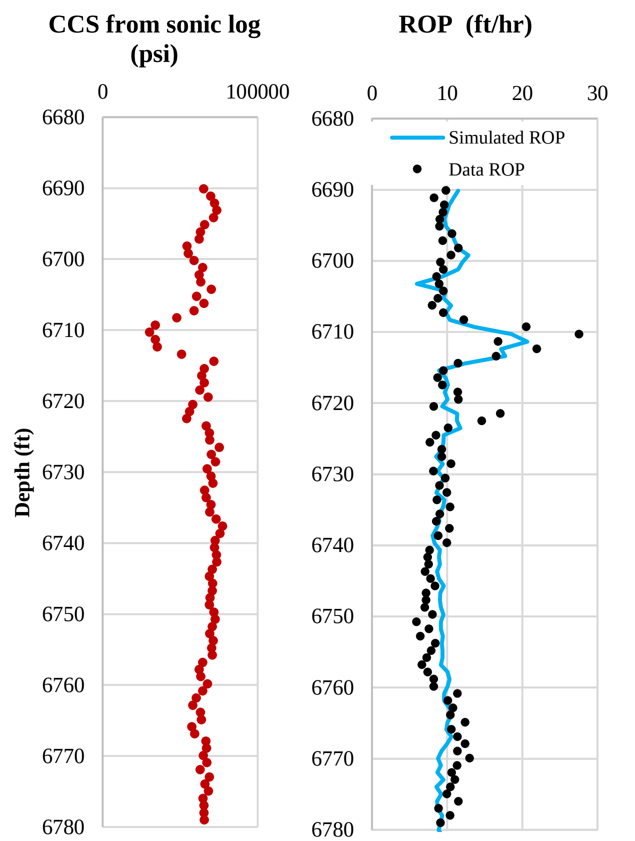

Fig 5. Simulated ROP versus measured ROP for Utah-Forge well 58-32 lower interval

Next, the drilling optimization software was applied to back-calculate the UCS from data ROP as if it was drilled in realtime. The back-calculated UCS was referred to as simulated real-time UCS. Note that the software uses the inverted ROP model for both the upper and lower intervals to calculate simulated real-time UCS.

Figure 6 shows the simulated real-time UCS and the data UCS for Utah Forge well 58-32 upper and lower intervals.

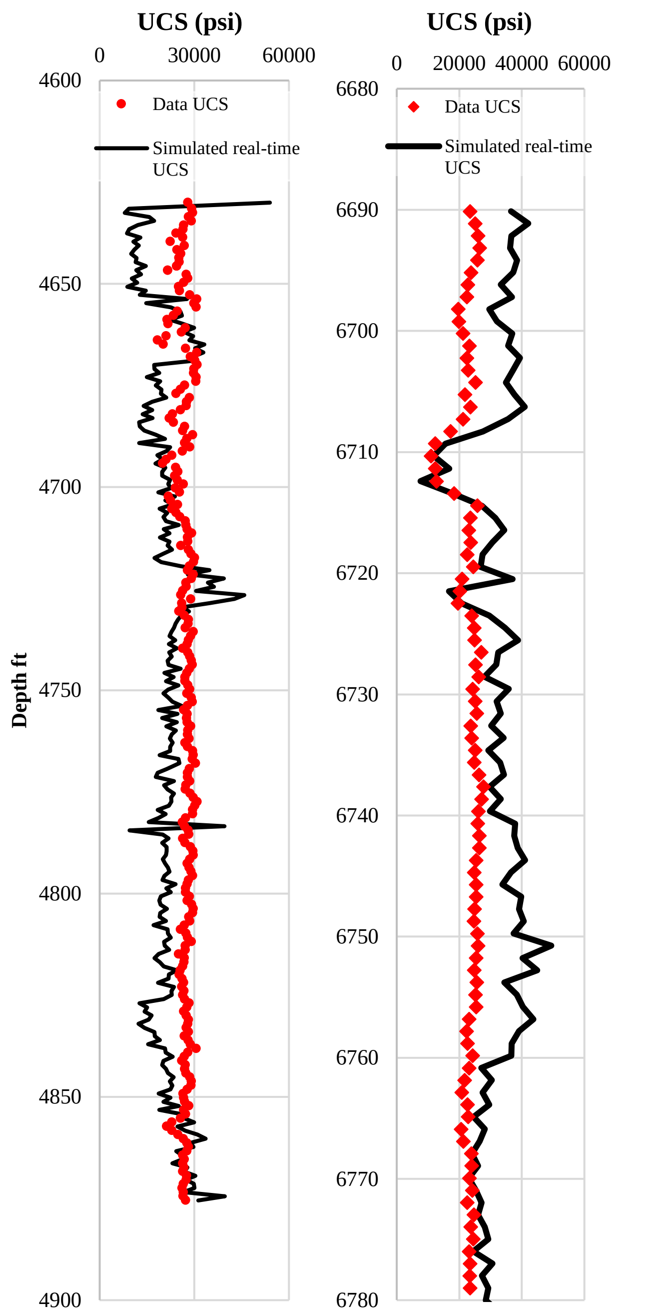

Fig 6. Comparison between real-time estimated UCS and data for Utah-forge upper (left) and lower (right) intervals

The discrepancy between the UCS values calculated from the sonic log (data UCS) and the drilling optimization system (simulated real-time UCS) is related to the real-time calculation of UCS based on ROP responses, which are sensitive to the drilling operational parameters. The drilling optimization system conducted real-time optimization for both intervals. The objective function was to maximize the instantaneous ROP for the next foot of drilling. The system can also use to minimize the Mechanical Specific Enegery as the objective function if selected. The cutter temperature limitation of 200 Celsius was applied in this study. The upper and lower limits for WOB were between 2,000 lbf to 50,000 lbf. Similarly, the upper and lower limit of 10 to 250 RPM was applied for RPM (see Table 1). The results are seen in Figures 7 through 10.

Table 1. The details in this study for optimization for both upper and lower drilling intervals.

	Upper Interval	Lower Interval
Bit diameter in inches (Db)	8.75	8.75
Number of blades (NOB)	7	7
Number of cutters (NOC)	34	34
Cutter diameter in inches (Dc)	0.51	0.51
Back rake (BR)	20	20
Side rake (SR)	1	1
PDC Thickness of cutter in inches (PDC_tt)	0.08	0.08
Initial Bit grade	0	1
BG out	1	2.5
Mud weight (ppg)	8.9	8.9
Optimization Goal	ROP maximization	ROP maximization
DE algorithm mutation rate	0.7	0.7
DE algorithm crossover rate	0.8	0.8
DE algorithm number of populations	50	50
DE algorithm iteration number	300	300
WOB lower limitation (lbf)	2000	2000
WOB upper limitation (lbf)	50,000	50,000
RPM lower limitation	10	10
RPM upper limitation	210	210
PDC cutter temperature limit (Celsius)	200	200

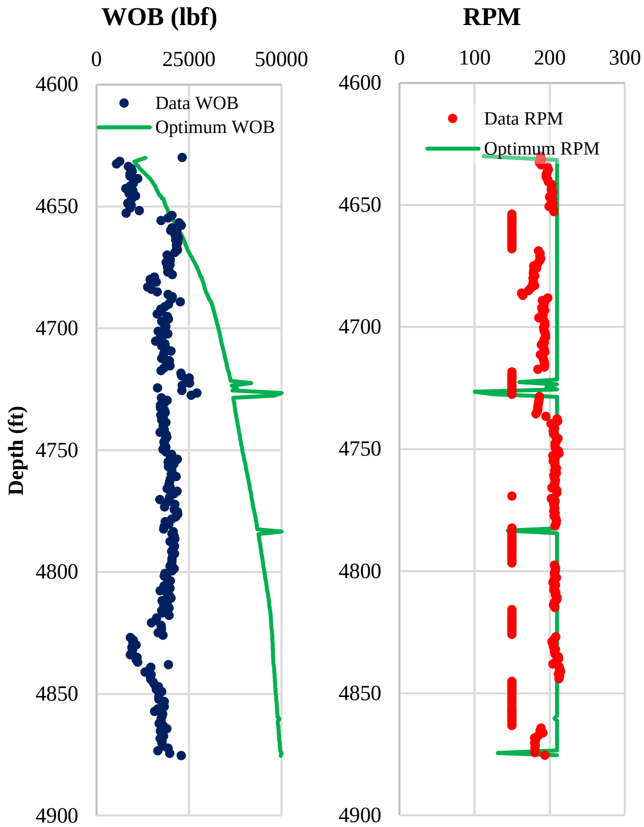

Fig 7. Comparison between Optimum operational parameters and data for Utah-forge upper interval

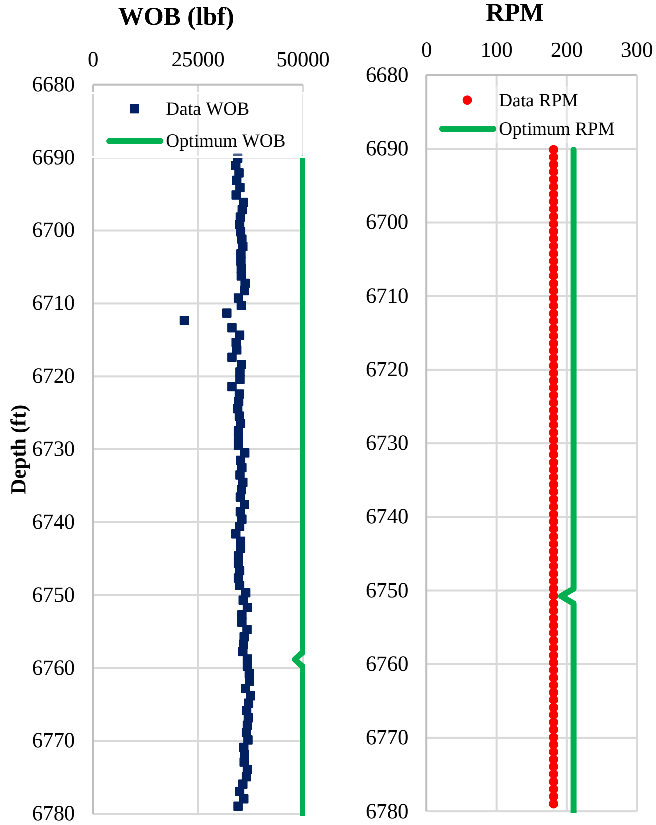

Fig 9. Comparison between Optimum operational parameters and data for Utah-forge lower interval

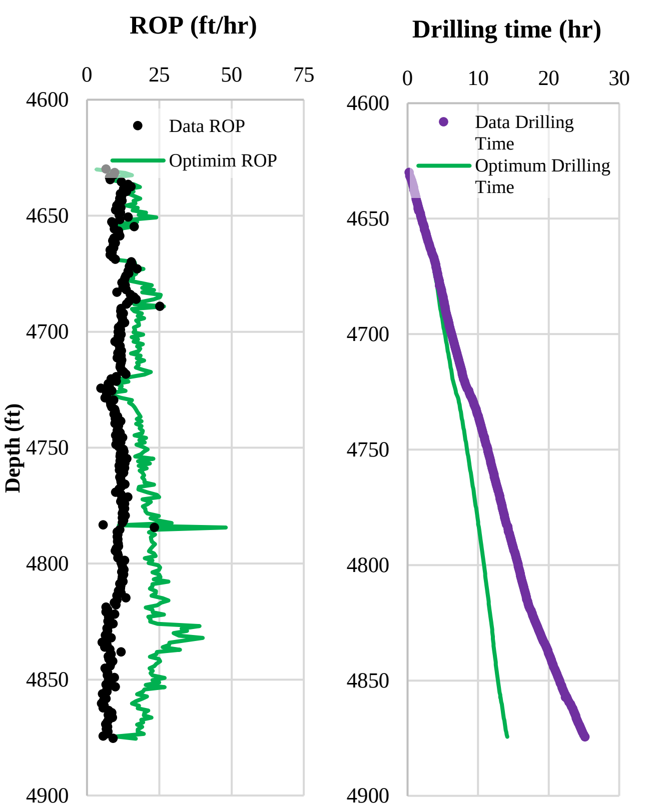

Fig 8. Comparison between Optimum ROP and drilling time parameters and data for Utah-forge upper interval

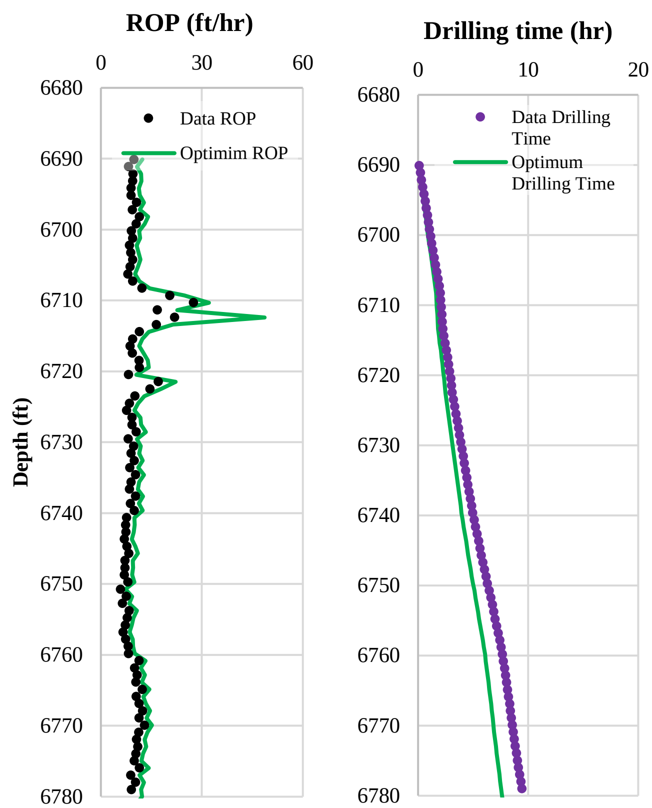

Fig 10. Comparison between Optimum ROP and drilling time parameters and data for Utah-forge lower interval

Three sections in the upper interval were drilled using sliding where the mud motor is rotating the bit without rotating the drill string. In the sliding sections, the WOB values were calculated for the three sliding sections using the standpipe pressure and flowrate to calculate the motor differential pressure relation to WOB from the rotating sections.

Based on the results, at the beginning of drilling the cutter wear flat area is too small (BG=0) which results in high cutter temperature. The WOB has a higher effect on cutter temperature compare to RPM based on the Glowka and Stone PDC cutter temperature model (1985), therefore the drilling optimization system starts drilling with minimum WOB at the beginning of the drilling interval while maximizing the RPM to achieve maximum instantaneous ROP (see Figure 7). As the cutters progressively get worn out, the wear flat area increases, and the cutter temperature decreases. Therefore, the drilling optimization system increases the WOB values to keep maximum instantaneous ROP while avoiding cutter accelerated temperature. Once the drilling optimization system achieved the maximum WOB limit (Figure 9), it drills the rest of the second drilling interval which was run with the same drill bit as the first section (Rerun with a BG of 1 at 6690ft) with constant maximum limits for both WOB and RPM (6690 ft to 6790 ft).

The irregularities of WOB and RPM in Figures 7 and 9 are related to the fact that the DE algorithm does not guarantee to find the absolute optimum values. The DE algorithm hyperparameters (mutation and crossover), population number, and algorithm iteration affect the searching ability in finding optimum values for WOB and RPM.

Based on the ROP model that was used in the drilling optimization system, the DE algorithm maximizes WOB and RPM to achieve a maximum possible ROP, while avoiding severe thermal accelerated wear. Torque limitations of a downhole motor if used will set the maximum power output. Otherwise, the max RPM is set by the rig (generally maximum of 180 RPM).

As it is seen in the drilling time plots in Figures 8 and 10, there is a potential for decreasing the drilling time for both drilling intervals (43% and 20%).

5. CONCLUSION

Drilling in geothermal resources is challenging due to the formation’s high temperature and rock strength. The drilling optimization system presented in this paper is designed to increase the drilling efficiency and reduce the drilling cost by increasing the instantaneous penetration rate of PDC bits. The system utilizes the intelligent searching method for optimization while taking the PDC bit cutter temperature into account. At the current time, the system does not integrate the vibrational effects and maximum torque limitations potentially from a motor, which will set further restrictions on the WOB and RPM operational window. The system can also be used to optimize for minimum MSE values instead of maximum ROP values and these results and comparison between the two approaches will be presented in future publications. The drilling optimization system benefits from the differential evolution algorithm (DEA) to achieve the optimum WOB and RPM in real-time for the next foot of drilling so-called real-time optimization.

6. FUTURE WORK

The drilling optimization system designed in this study needs to incorporate several modules to achieve its full potential for drilling optimization and simulation. In the deviated and horizontal wells, the effective weight on bit is less than WOB recorded at the surface. Therefore, to estimate an accurate WOB, the downhole weight on bit models should be applied for surface WOB adjustment.

In this study, 50,000 lbf and 250 RPM were used as the upper limit of WOB and rotational speed respectively. Stick-slip, wobbling, and drillstring vibrations are among major challenges in drilling hard formations. The above-mentioned issues can result in the failure of drilling components which consequently can increase the nonproductive time (Al Dushaishi and Stutts, 2020). At high WOB values, the stick-slip could be an issue and should be considered as a constraint for choosing an optimum value. WOB and RPM affect the stick-slip severity, therefore, stick-slip severity models should be incorporated into the system to avoid the unsafe combinations of WOB and RPM that could result in severe vibration issues.

The simulation here assumed 100% efficiency for bottom hole cleaning. A hydraulic model will be included in the ROP model but is not as important in the geothermal drilling as long as ROP is below 35-40 ft/hr and as a rule and the bit hydraulic horsepower per square inch is at 1.0. The optimization results for operational parameters in this study at this time are theoretical and the future system will add further limitations on the WOB and RPM operational window including vibrations and equipment limitations.

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