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Optimization of Drilling Performance Based on an Intelligent Drilling Advisory System

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Abstract

Optimization of drilling parameters during drilling operations is a key component to obtain maximum rate of penetration (ROP) as well as minimizing the drilling cost. Advancement in computer technologies and communication are among the most important factors that can contribute to drilling optimization. In the current work, a novel rig advisory system is developed to continually improve ROP and the drilling performance. Conventionally, drillers apply drilling parameters (weight-on-bit, rotary speed and pump rate) according to past experience or to parameters specified in the drilling program. These parameters are usually kept constant over a long interval regardless of the formations being drilled. However, it is well-known that keeping constant drilling parameters to drive the bit will lead to redundant depth of cut (DOC), inducing stick-slip vibration that leads to low ROP, higher drilling specific energy (DSE), and potential damage to the bottom-hole assembly (BHA).

An intelligent drilling advisory system (IDAS), based on a soft-closed-loop solution with multiple regression analysis called optimum parameters global retrieval, has been established. Integrated with machine-learning methodology (Principal component analysis), the response of the drilling parameters with lithology changes was analyzed in real time. Additionally, the optimum control parameters direction were obtained from the gradient search and decision tree algorithms. This system monitored the relationship between the ROP and input energy delivered to the bit in real time, and calculated the optimized drilling parameters. The work presented how the IDAS procedures were applied in China, how the data was interpreted, and how optimum working parameters were obtained to guide drillers to improve drilling performance and reduce non-productive time (NPT).

IDAS has been introduced to hard formation drilling, which proved to be a success in real-time advisory aiding drillers applying proper working parameters for maximum ROP. Field applications of IDAS guidance showed significant ROP improvement compared to that of conventional drilling.

As an effective tool for further achieving the optimum DOC, a novel control system achieved satisfactory outcomes that overcome the drilling challenges in Saudi Arabia and China, which will serve as a step forward towards automated drilling operations.

Introduction

The cost of drilling wells increases with deeper formation, due to lower ROP and more drilling time by downhole limiters, with increased formation strength and bit wear, insufficient hole cleaning, high vibrations levels, and poor mud properties. However, it is not easy for the driller to identify the conditions limiting the ROP, so improper drilling parameters may cause inadequate or excessive cutting to the rock, resulting in low cutting efficiency. These may include bit balling from insufficient hydraulic pressure, or cutter damage from excessive impact.

An innovative recently deployed real-time driller indicator called the Intelligent Drilling Advisory System (IADS) was developed to inform drillers of optimal WOB, rotary speed, and mud flow rate to penetrate rock and achieve higher ROP and longer bit runs. The optimized drilling parameters showed in the IADS are calculated and updated using a soft closed-loop solution, which monitors the ROP and energy input to the bit in real-time by means of a mud logger and top drive system controller on the rig site, and calculates the optimized drilling parameters by maintaining an optimal relationship between ROP and energy input. If the ROP is under expectation, it automatically evaluates the new conditions, such as the lithology of formation change, bit wear, and drill string vibration, etc., and updates the optimal parameters by maintaining a proper relationship between ROP and energy input. The following novel features of the IADS significantly improve drilling performance:

- A combination of evaluation factors such as DSE and DOC, etc., which may be more advantageous to drilling performance. Simple optimization for ROP improvement may not achieve maximum potential drilling performance given current drilling technologies and geology, and the consideration of ROP over all over factors generally leads to serious bit wear.
- The system and solutions are capable of recommending operational changes during drilling operations while the limiter occurs – referred to as a "founder point." The limiter identification utilizes probability distributions to determine whether the incoming data stream falls outside a specified estimated probability distribution significance level. An outlier in comparison to the probability distribution space may indicate a change in drilling conditions, allowing the driller to periodically detect environmental changes during drilling.

This paper mainly describes the optimization model to recommend optimal parameters in response to changes in drilling environment, and applies the system to improve drilling performance.

Optimization Mechanism and Workflows

The relationship among ROP, DSE, and DOC creates three regions in any rock. As shown in Figure 1, region 2 is located in a highly effective cutting region; the others produce inadequate or excessive potential cutting performance. Tracing parameter deviation, lithology change plots and limiters such as bit balling and vibrations can be identified in real-time during drilling operations. Moreover, the parameters are updated in an optimal direction to maximize potential performance in line with region 2 (Dupriest and Koederitz 2005).

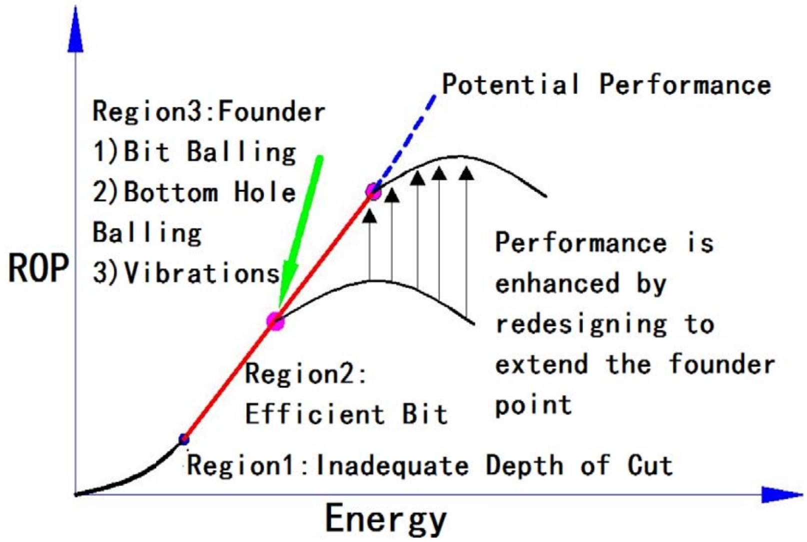


Figure 1—The relationship of ROP and energy input

At the start of drilling, the system gathers data related to the drilling parameters. Meanwhile, information prompt is triggered, telling the driller to scan the overall drilling parameter space designated in the drilling program. The specific process is normally to check whether the quantity and quality of the drilling parameters are sufficient for the subsequent statistical analysis. The requirements include at least two of the controllable parameters such as WOB, RPM, or flow rate, and at least one uncontrollable parameter such as bit torque to characterize downhole environment changes. Generally, the system gathers data over a certain interval such as 3-5m, depending on ROP. When the data window length lies within some threshold amount, global optimization is triggered, based on the "Cubicinterp" 3-D surface fit method. The objective function maximizes DOC or minimizes DSE, etc. Once optimal results are recommended, a decision tree is run to validate the recommendation. Once validation is passed, the result is displayed. If the validation fails, the downhole environment detection engine is launched to check whether the bit has encountered a substantial formation change, in which case the data window is refreshed and global optimization may be restarted. Alternatively, the local retrieval process may be triggered. Finally, the optimal operating parameters are derived by the system.

Drilling Optimization Models

Drilling performance evaluation models

Rock-breaking efficiency evaluation model. The concept of DSE illustrates that the energy required to drill a given volume of rock correlates with the efficiency of the bit in destroying the rock. When the bottom-hole assembly is equipped with a mud motor, the motor transforms the hydraulic power into mechanical energy to break the rock. The DSE model is expressed as follows (Cui et al. 2014):

$$DSE = EFF_M \times (\frac{4 \cdot WOB}{\pi D_b^2} + \frac{480 \cdot \Delta P_{pdm}(RPM_s + k_n Q)(\frac{T_{\max}}{\Delta P_{\max}} \Delta P_{pdm} + T_{top})}{D_b^2 ROP}) \tag{1}$$

where K_n is the mud motor speed to flow ratio (unit: rev/l), $T_{\max}$ is the maximum rated torque of the mud motor (unit: N.m), $\Delta P_{\max}$ is the maximum rated differential pressure of the mud motor (unit: MPa), ΔP_{pdm} is the differential pressure (unit: MPa), Q is the flow rate (unit: l/s), D_b is the bit diameter (unit: mm), and ROP is the rate of penetration (unit: m/hr).

Under field conditions, due to wellbore friction and vibration, etc., energy efficiency is low, generally 30-40%. Therefore, the bit's energy efficiency, denoted as EFF_M, is generally equal to 35% of ongoing operations.

Torsional vibration evaluation model. The dynamic state description equation of the drill string was developed on basis of Newton's equations of motion. The equation ignores the torque generated by gravity (Richard et al. 2002).

$$\tau - \rho J \ddot{\alpha} = \theta_{\mathrm{T}} \cdot t \tag{2}$$

Where t is the unit vector along the trajectory of well hole, τ in the internal element force (unit: N), $\ddot{\alpha}$ is angular acceleration (unit: radians/s^2), ρ is the density (unit: kg/m^3), J is the polar moment of inertia (unit: m^4), and θ_{T} is the external torque vector (unit: N.m).

When torsional vibration occurs, its dynamic state vector, including torque and torsional degree, is transmitted along the drill string from bit to the surface. The vectors on each element are derived from a transfer matrix model. The model for evaluation of torsional vibration is developed as follows:

$$\begin{bmatrix} \alpha_{\Omega}(i) \\ \tau_{\Omega}(i) \end{bmatrix} = \begin{bmatrix} \cos(\frac{\Omega}{\sqrt{G/\rho}} \cdot l_i) & \frac{1}{\Omega\sqrt{G\rho}J_i} \cdot \sin(\frac{\Omega}{\sqrt{G/\rho}} \cdot l_i) \\ -\Omega\sqrt{G\rho}J_i \cdot \sin(\frac{\Omega}{\sqrt{G/\rho}} \cdot l_i) & \cos(\frac{\Omega}{\sqrt{G/\rho}} \cdot l_i) \end{bmatrix} \cdot \begin{bmatrix} \alpha_{\Omega}(i-1) \\ \tau_{\Omega}(i-1) \end{bmatrix} \tag{3}$$

Where α is the torsional degree of the element (unit: radians), τ is the torque of the element (unit: N.m), G is the shear modulus of the element (unit: Pa), and l is the length of the element (unit: m).

Drilling performance evaluation model. The IADS is utilized to directly optimize one or more drilling performance evaluation indicators by analyzing the relationships among controllable drilling parameters. In order to simultaneously achieve maximum ROP and depth of cut per revolution (DOC), and minimize DSE and stick slip severity, an objective function is developed to analyze the relationships between drilling performance and controllable drilling parameters, as follows:

$$\mathrm{Obj}_{(ROP,DOC,DSE,SS)} = \frac{1 + \Delta ROP / ROP_{i-1} + \Delta DOC / DOC_{i-1}}{1 + \Delta DSE / DSE_{i-1} + \Delta SS / SS_{i-1}} \tag{4}$$

Where

$$DOC = 16.67 \cdot ROP / RPM \tag{5}$$

The unit for DOC is millimeters/revolution. The objective function value is maximized through adjacent time slots (1-2min) during drilling operation. The higher the value, the better the outcome.

Global and local retrieval models for optimal parameters

Global retrieval model. The relationships between the controllable drilling parameters and drilling performance functions are derived on the basis of cubic interpolation. Meanwhile, the optimal points are found through 3-D surface fitting through the gathered dataset. Figure 2–3 illustrates the simulation results utilizing both minimum DSE and maximum DOC objective functions. After the global retrieval process is executed 5-10 times, a decision tree method is utilized to evaluate whether the optimal results meet the requirements. The method is detailed in Figure 4. Once the percentage of recommendations passes a threshold value, the optimal parameters are sent to the driller, or else the downhole environment detection model is executed.

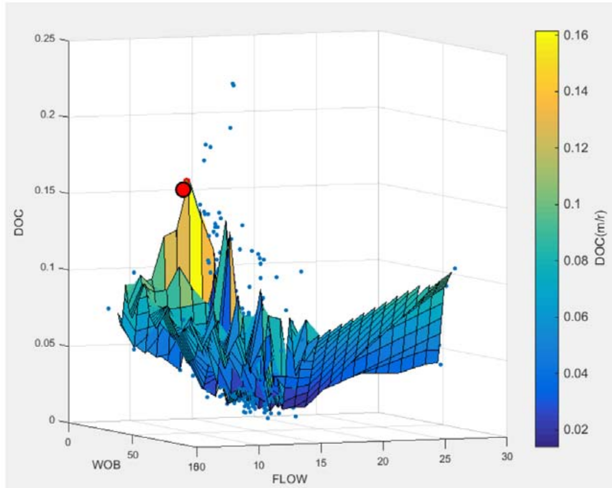


Figure 2—The global retrieval simulation results (DOC-WOB-Flow rate)

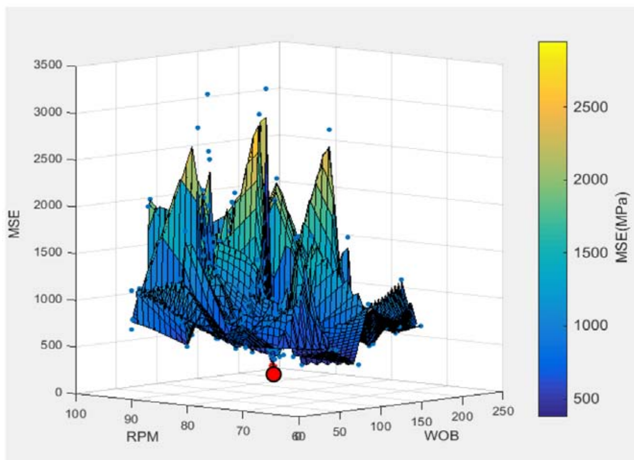


Figure 3—The global retrieval simulation results (DSE-WOB-RPM)

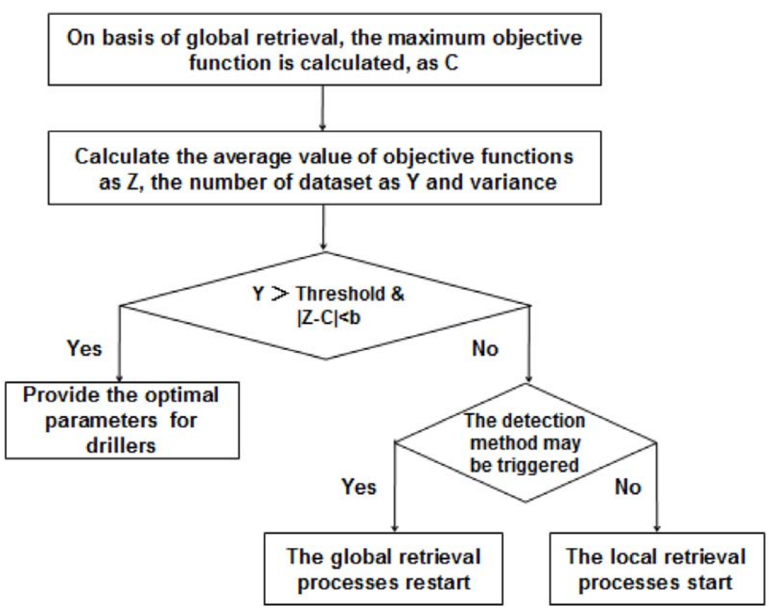


Figure 4—The workflow for decision tree method

Downhole environment detection model. IDAS compares the datasets from adjacent time slots to identify correlations among of drilling parameters using principal component analysis. When the incoming dataset falls outside a specified significance level of the possible distribution, such as outside principal space, the residual threshold indicates a change in formation or drilling environments. The concept of principal component analysis is diagonalization of the covariance matrix. The eigenvectors are calculated based on the diagonal line, and some dominant principal with great value containing more energy is utilized to characterize the drilling environment.

Assuming the analysis vector has p dimensions,

$$x = (x_1, x_2, ..., x_p)^T \tag{6}$$

where x represents the objective function and drilling parameters such as WOB and RPM, etc.

Assuming the analysis vector has n samples,

$$X(i) = (x_{i1}, x_{i2}, ..., x_{ip})^T \tag{7}$$

where the time i denotes an interval or time slot, $i = 1,2,\ldots, n$; $n \geq p$.

The covariance matrix is as follows:

$$C = \frac{Z^T Z}{n-1} \tag{8}$$

$$Z_{ij} = \frac{x_{ij} - \bar{x}_j}{s_j}, i = 1, ..., n; j = 1, ..., p \tag{9}$$

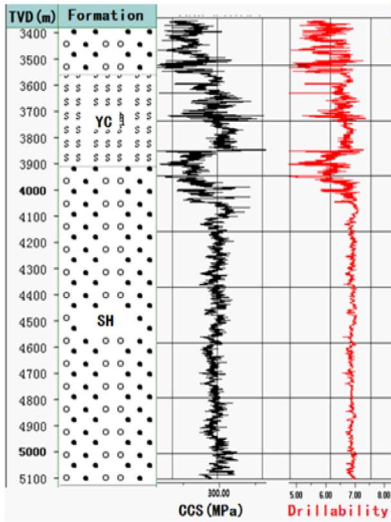
Where,

$$\bar{x}_j = \frac{\sum_{i=1}^{n} x_{ij}}{n}, s_j = \sqrt{\frac{\sum_{i=1}^{n} (x_{ij} - \bar{x}_j)^2}{n-1}}.$$

Solving equation (8), p denotes the number of eigenvalues for the data within the analysis window to be rendered. Eigenvectors with values greater than one are regarded as principal vectors to describe the downhole environment. The newly gathered data should lie within the principal space of the previous time slot. Once the drilling environment changes, and then the principal space may change. The detection model is as follows:

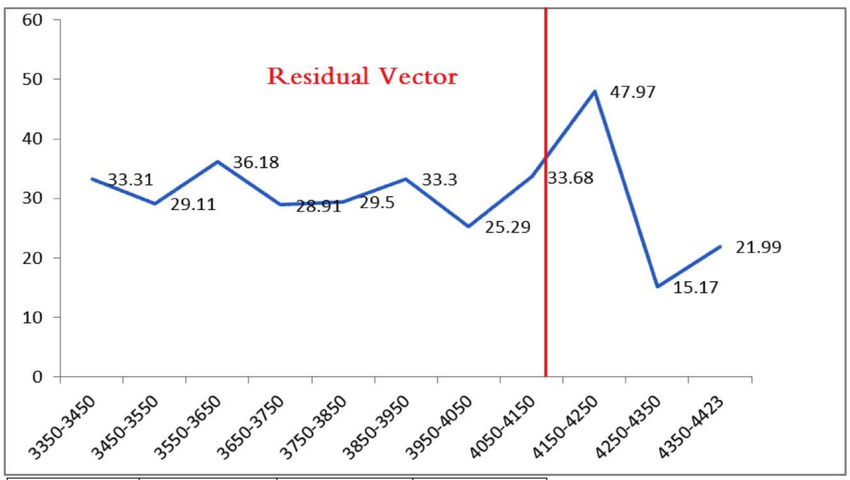
$$D(i) = X(i) - \sum_{p=1}^{m} \langle X(i) \cdot F_k \rangle F_k^T \tag{10}$$

Where, m denotes the number of principal vectors for the last time slot. F_k is one of principal spaces of the previous time slot. The dot product is the projection of the gathered data vector X(i) and the principal vector F_k. When the D(i) change rate (residual) exceeds 30%, the alarm is triggered, informing the driller of a possible downhole change. Figure 5–6 displays simulation results for lithology change.



Geology Division	Thickness (m)	Lithology
DLK	396	Grey mudstone, grey argillaceous siltstone, purple mudstone
YC	344	YC4：glutenite, sandstone YC3:basalt, tuff CCS：300MPa Drillability：6-7
SH	816	Glutenite and mudstone CCS：200MPa Drillability：7-8

Figure 5—The geology division for the simulation formation change detection



Analysis window	Diagnosis window	Residual vector	Formation
3250-3650	3650-3750	28.91	YC
3350-3750	3750-3850	29.50	YC
3450-3850	3850-3950	33.30	YC
3550-3950	3950-4050	25.29	YC
3650-4050	4050-4150	33.68	SH
3750-4150	4150-4250	47.97	SH
3850-4250	4250-4350	15.17	SH
3950-4350	4350-4423	21.99	SH

While the formation change from YC to SH, there is a significant increasing for residual change rate. The simulation result verifies the the sensitivity of detection method for formation change.

Figure 6—The geology division for the simulation formation change detection

Local retrieval model. Local retrieval supplements global retrieval. The two work together to optimize drilling by correlating control parameters to more drilling performance indexes. Global retrieval is able to scan the entire operating parameters space designed by the drilling program; local retrieval is well-suited to optimize the objective function within a subset of operating parameters. Local retrieval runs after global retrieval, at the beginning of the drilling operation, in serial mode. Once global retrieval is completed, local retrieval may then be run continuously. In the event of no change in downhole environment for a long interval, or a sudden significant change, global retrieval is then restarted.

On basis of the least squares fit, more controllable drilling parameters have been correlated to objective functions incorporating ROP, DSE and DOC (Cui et al. 2014; Dunlop et al. 2011).

$$\begin{cases} c_j = \dfrac{(f(x), \varphi_j(x))}{(\varphi_j(x), \varphi_j(x))} = \dfrac{\sum_{i=0}^{m} \omega_i f(x_i) \varphi_j(x_i)}{\sum_{i=0}^{m} \omega_i \varphi_j^2(x_j)} \\ s^*(x) = \sum_{j=0}^{n} c_j \varphi_j(x_j) \end{cases} \tag{11}$$

where $f(x)$ is the depth of cut, mm/revolution or WOB (unit: kN), x_i is WOB, kN or torque (unit: kN.m), $S^*(x)$ is the fit function for depth of cut vs. WOB & WOB vs. torque, ω_i is a constant (generally 1), c_j is the function coefficient, and $\varphi_j(x_j)$ is the cardinal interpolation function, j = 1, 2. A series of objective ROP and DSE contours correlating with operational parameters are obtained accordingly. ROP and DSE improvements are based on the optimal direction of the contours, which in some implementations may then provide the operational recommendations. Figure 7 shows an optimization simulation result utilizing offset well data.

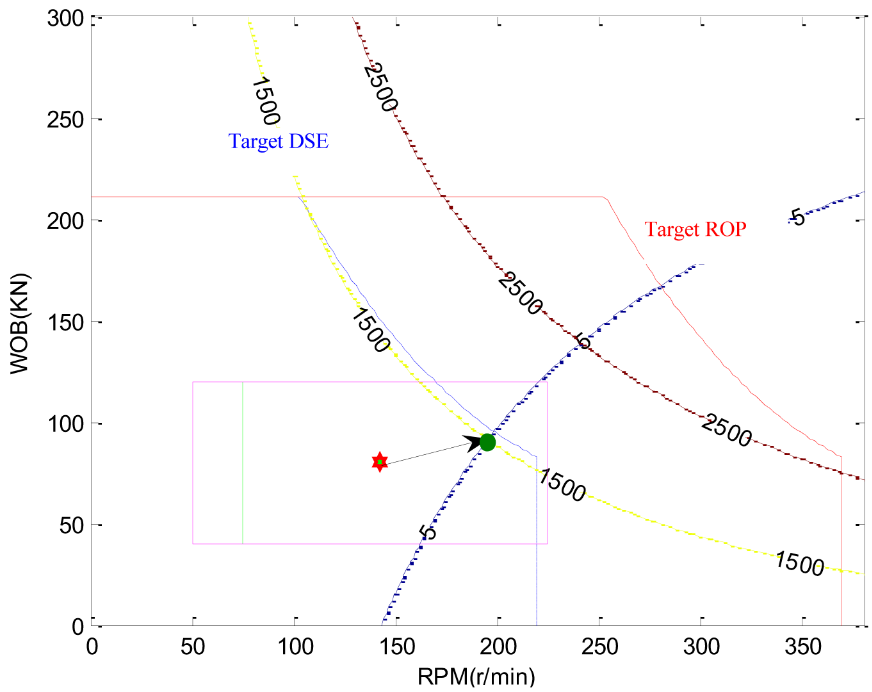


Figure 7—The simulation result for the local retrieval method towarding the optimal parameters direction

Finally, a Kalman filtering algorithm is also used to enhance the data quality for optimization analysis. The data stream processed for noise mitigation is forwarded to the above models.

System architecture

IADS is an innovative real-time drilling optimization system which gives driller WOB, rotary speed, and mud flow rate values adequate for rock penetration in order to maximize ROP and bit runs. The optimized drilling parameters shown in IADS are calculated by modules monitoring shifts in drilling energy, changes in lithology, and ROP, etc., through rig instrumentation. The workflow is shown in Figure 8. The IADS system architecture includes four main modules: data gathering, rock-breaking efficiency monitoring, vibration strength estimate, and drilling advisory.

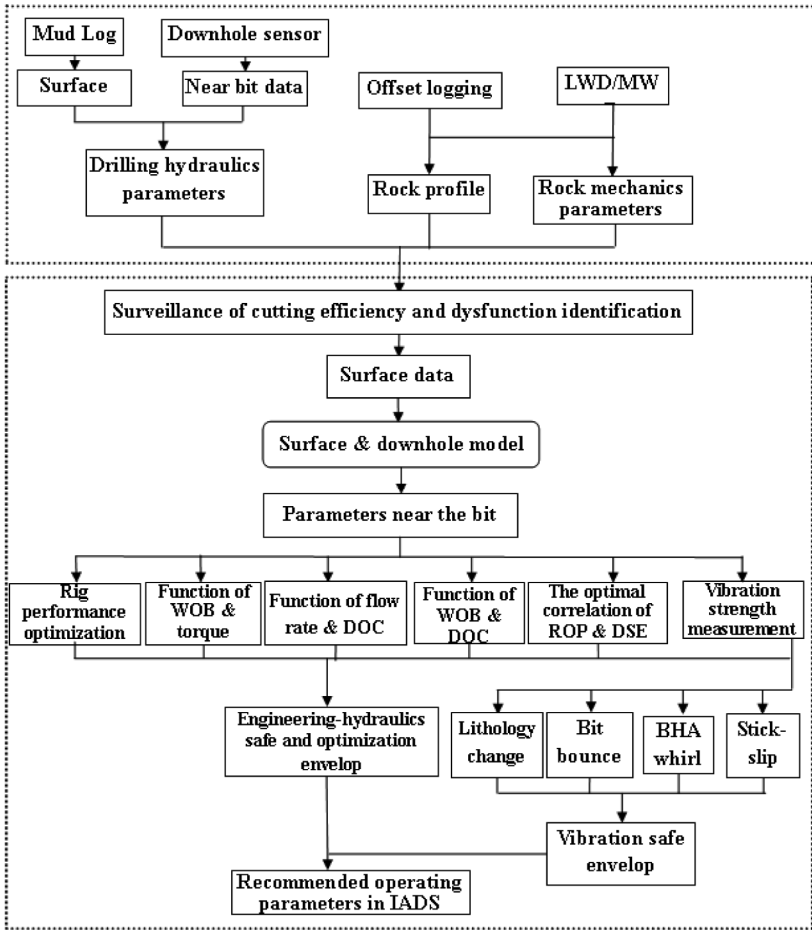


Figure 8—The work flow chart for IADS

The real-time data gathering module

- Provides real-time data for drilling surveillance and optimization.
- Acquires real-time source data in accordance with the WITS format, and stores them in the database.
- Automatically detects information regarding SDI communications and operational status.
- Provides diagnostic alarms in the form of an indicator. A continuously blinking indicator shows that the system is communication with the data provider. If the data service is interrupted, the blinking indicator disappears.

The rock-breaking monitoring module

- Calculates MSE_{min}, DOC, and DSE and correlated drilling performance measurements in real time.
- Displays parameters on the driller interface as curves to analyze the drilling process in real time.
- The primary value-added benefits of the optimization module are timely DSE and DOC values.
- MSE_{min}, resulting from offset well CCS, etc., is one of the optimization criteria used to evaluate drilling efficiency.
- Data trends alert the driller to the onset of changes in formation or other drilling conditions such as bit balling, bottom balling, and vibrations.

The vibration strength estimate module

- Simulates working stress and side loads on the BHA before drilling starts.
- Calculates critical speeds to avoid based on the BHA and drilling conditions, preventing vibration damage.
- Designs down-hole tools fit for the purpose.
- Estimates vibration strength in real time to ensure that ROP is free from critical vibrations.

The drilling advisory module

The advisory module optimizes distribution of ROP and DSE and recommends optimal operating parameters for drillers. Once the system is launched, the module is then automatically shown to the driller, as shown in Figure 9.

Figure 9—The main interface for driller

- The "Configuration" menu item includes well information, communication setup, and formation data load.
- "Model selection" allows for selection of drilling methods including mud motor drilling, gas hammer drilling, and reaming, etc.
- The "Parameter monitor" provides a primary view of real-time drilling parameters. Real-time display and the calculation parameter drop list are situated in this module.

The middle row displays application information including well name, oilfield, and optimization section. The right of the row displays the downhole situation in real time, such as drilling, bit balling, and blank nozzle, etc. The far right of the row displays the drilling efficiency score. The higher the green bar is, the better the efficiency.

The main screen includes four novel, intuitive gauge dashboards, respectively indicating WOB, rotary speed, and pump stroke. Each gauge consists of two pointers: a needle, colored red, denoting the current parameter, and an arrow, colored blue, indicating the optimal set point. The three colored band backdrops of the gauge show vibration levels. The green one illustrates low vibration levels, with little impact performance. The red band backdrop indicates high levels of vibration, with potential to damage the BHA. With respect to bit life, the red needle should be controlled within the green color band, which follows the blue marker set points to achieve optimal cutting efficiency.

Field test cases

IADS was successfully applied in the MX009-H9#, Southwest Oil & Gas field in China from May 7 to 22, 2018. The bit run was 459m from m.d. of 3538m to 4037m.

BHA data

Φ8-1/2″GS1635R PDC +Φ6-5/8″Mud-motor+Φ6-5/8″VibrationRecorder+Φ6-5/8″NMDC+Φ8-2/5″STB +Φ6-5/8″DC+Φ6-5/8″PV+ Φ6-1/2″DC×12+Φ6-1/2″JAR+Φ5″HWDP×3 +Φ5″DP

Performance evaluation strategy

In order to evaluate the performance of IADS compared to conventional methods, the hole section was drilled conventionally during the daytime from 8:00 am to 20:00 pm, while the hole section was drilled with IADS guidance, using same bit, BHA, mud properties, and formation at night from 20:00pm to 8:00am.

Critical vibration identification and mitigation

From 3500m to 3610m, the formation is comprised of mudstone. The initial WOB was increased from 80kN to 120kN, and the rotary speed was 50RPM with 25l/s flow rate. In IADS, the stick-slip strength curve increased, showing the occurrence of critical stick-slip and bit bounce, as shown in Figure 10. Meanwhile, the optimized WOB was set to 100kN, and the blue maker for rotary speed increased to 60RPM, with the flow rate increased to 27l/s, shown in Figure 11. As the parameters were adjustment in line with the blue markers, energy consumption immediately declined below 500MPa, with stick-slip strength mitigation.

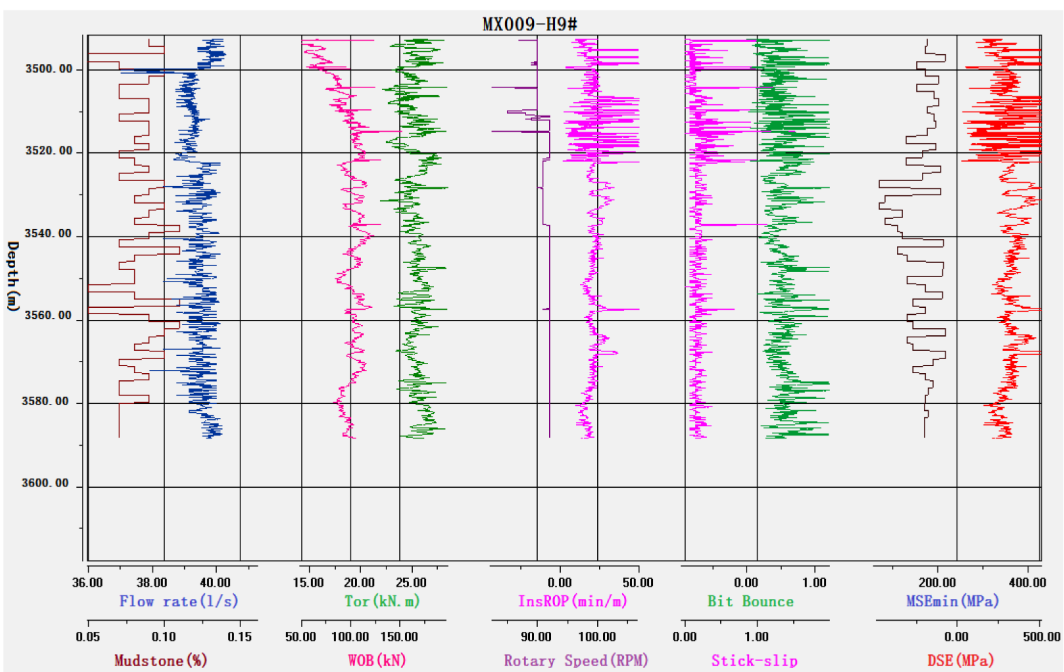


Figure 10—Vibration identification and mitigation

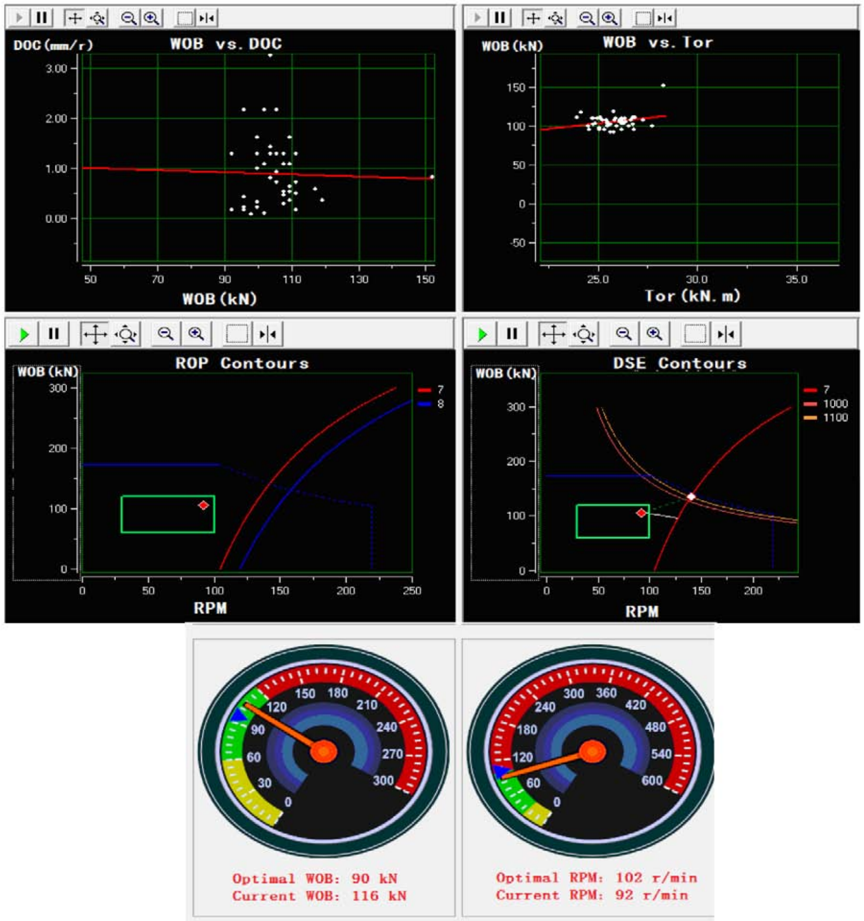


Figure 11—The optimal recommendation provided by IADS for mitigating stick-slip

Lithology change identification

As the bit ran from a depth of 3980m to 3996m, the CCS of the formation – that is, the MSEmin curve significantly increased to around 300Mpa, as shown in Figure 12. The IADS indicated the formation change, telling the driller to increase WOB and rotary speed or flow rate. According to the upwards cuttings, the lithology changed from limestone to black mudstone, as shown in Figure 13. According to actual field records, the geology changes at depth of 3987m. After parameter adjustment, the DSE curve decreased, as did drilling time per meter.

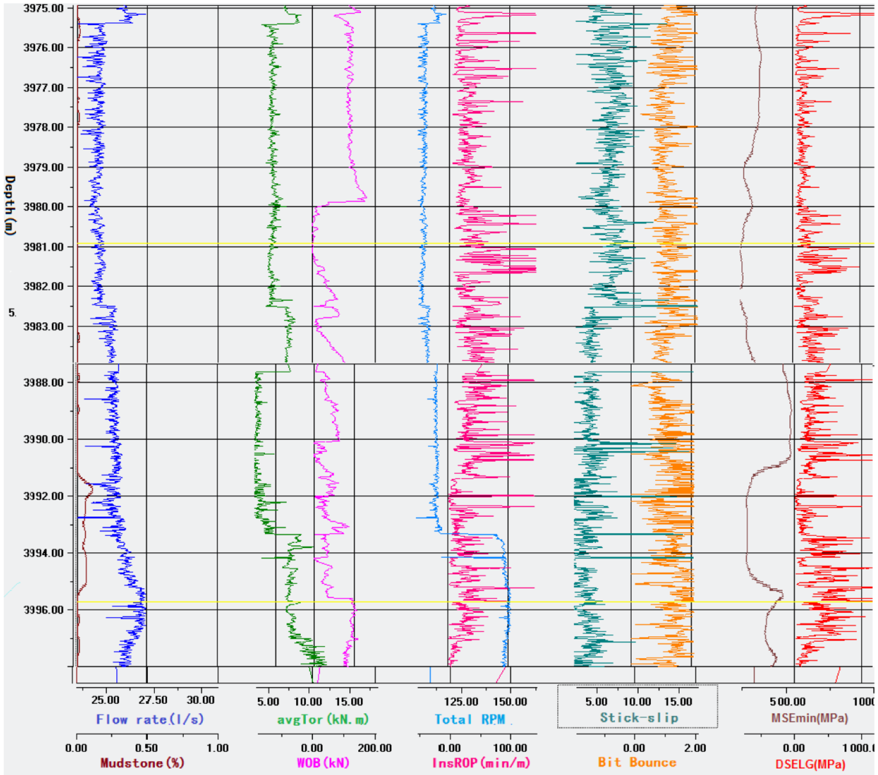


Figure 12—The formation change identification with drilling performance inprovements

Figure 13—The lithology change from T_1f^2 to P_2ch

Bit wear identification

From the depth of 4010m, the geology changed from P_2I to P^1m^4. However, in order to achieve higher ROP using the same parameters applied in the P_2ch division, the driller did not follow the recommendations from IADS. Although higher ROP was achieved, as a result of neglecting WOB and RPM had exceeded thresholds, critical vibration destroyed the cutters. As shown in Figure 14, the degree of wear was over 50% when the bit was pulled out of the hole.

Figure 14—The comparison of bit RIH and POOH

The downhole vibration memory sub records the triaxial acceleration of the bit during drilling in real-time at a sampling rate of 40Hz. The red line in Figure 15 indicates the drilling time per meter as the geology changed P_2I from to P^1m^4. The blue colored dots show the lateral vibration on the BHA. After the bit reached the P^1m^4 formation, the CCS of the formation decreased compared to the P_2I formation. Even though the maximum ROP was achieved, the cutters over-penetrated into the formation, leading to serious wear. The lateral vibration acceleration had exceeded 10g. Over about 150m, bit wear reached a critical degree, leading to inadequate depth of cut. Thus, vibration decreased, but the drill time curve increased sharply. The bit was subsequently pulled out of the hole.

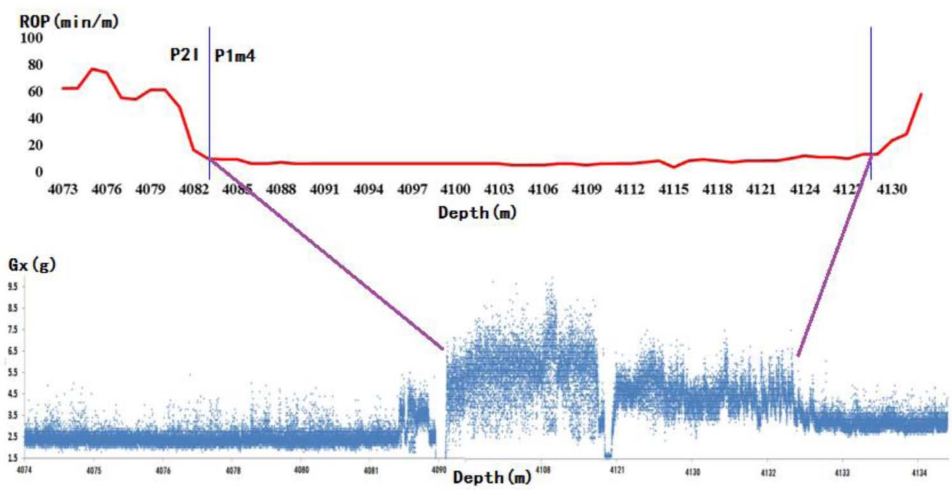


Figure 15—The over high ROP resulting the critical downhole vibrations

The vibration data verified that excessive ROP does not improve rock breaking efficiency. On the contrary, it generally comes at the expense of bit life.

Drilling performance evaluation

Vibration mitigation

Figure 16–17 shows the actual RPM fluctuation and axial and lateral acceleration measured at the bit using downhole sensors. The data stream illustrates the vibration strength of the shift change, at intervals, relying on IADS, but the adjacent interval without relying on its recommendations. Comparing results from the chart (which displays the drilling performance improvement from IADS) in the intervals which followed the IADS recommendations, optimization reduced the tendency for critical vibrations.

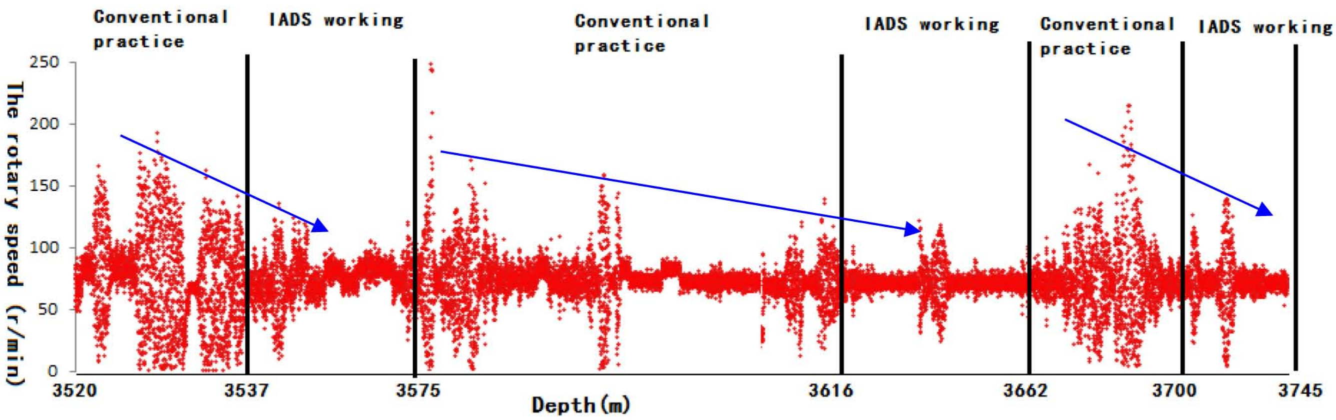


Figure 16—Vibration mitigation results for stick-slip

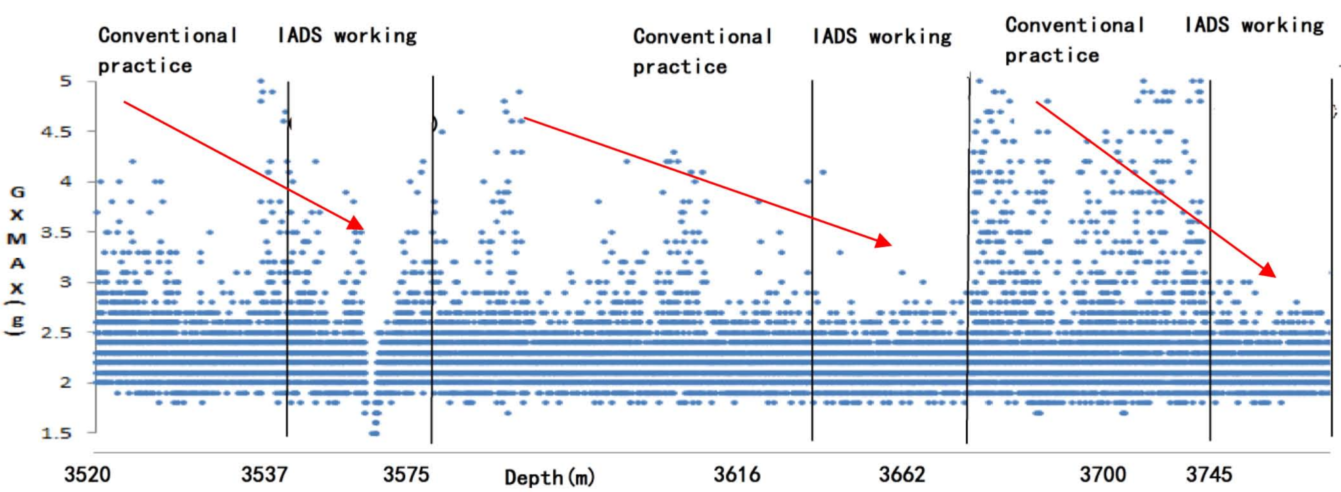


Figure 17—Vibration mitigation results for lateral space

Application results

For the T_1f^2 geology division, 121m was drilled using IADS guidance, with penetration time of 27.58hrs, and ROP of 4.39m/h. By contrast, 78m was drilled conventionally, with penetration time of 21.44hrs, and ROP of 3.64m/h. Meanwhile, in the P_2ch, 52m was drilled using IADS guidance, with penetration time of 6.47hrs, and ROP of 8.04m/h, while 69m was drilled conventionally, with penetration time of 10.44hrs, and ROP of 6.61m/h. Table 1 shows the performance on basis of the shift changes.

Moreover, the rock strength in both the mauve mudstone and limestone was about 200-250MPa. The average energy utilized to break the rocks was around 400MPa for the IADS guidance section, and the variation was less than 10%, indicating efficient cutting. However, the energy applied in the conventional sections varied more, with an average value of 560MPa, nearly three times the rock strength itself. In the T_1f^2

and P_2ch divisions, IADS guidance showed 24.59% gains in average ROP compared with the conventionally drilled sections, and average DSE decreased 33.1%. See Figures 18–19.

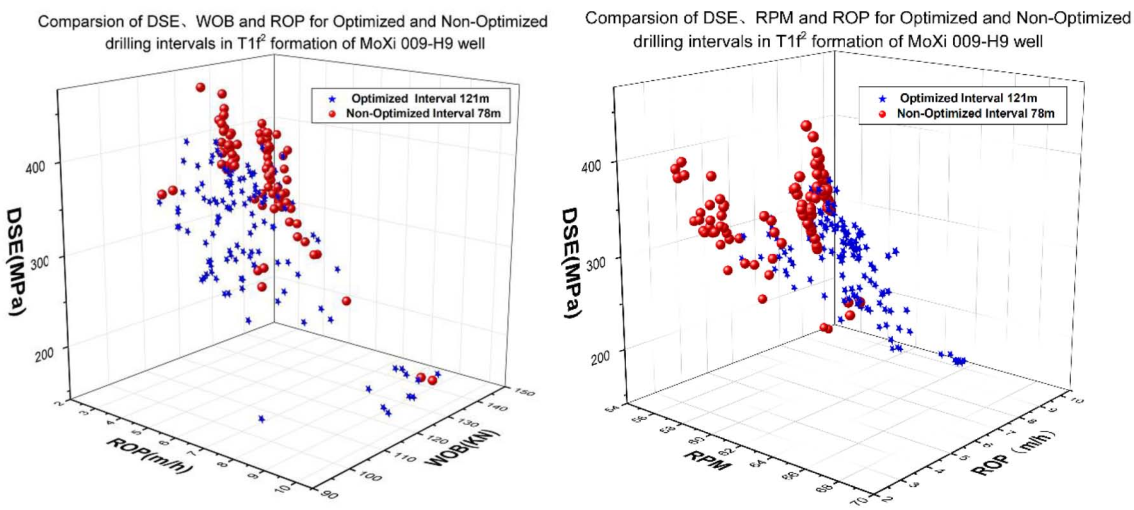


Figure 18—Drilling improvemnts in T_1f^2 formation

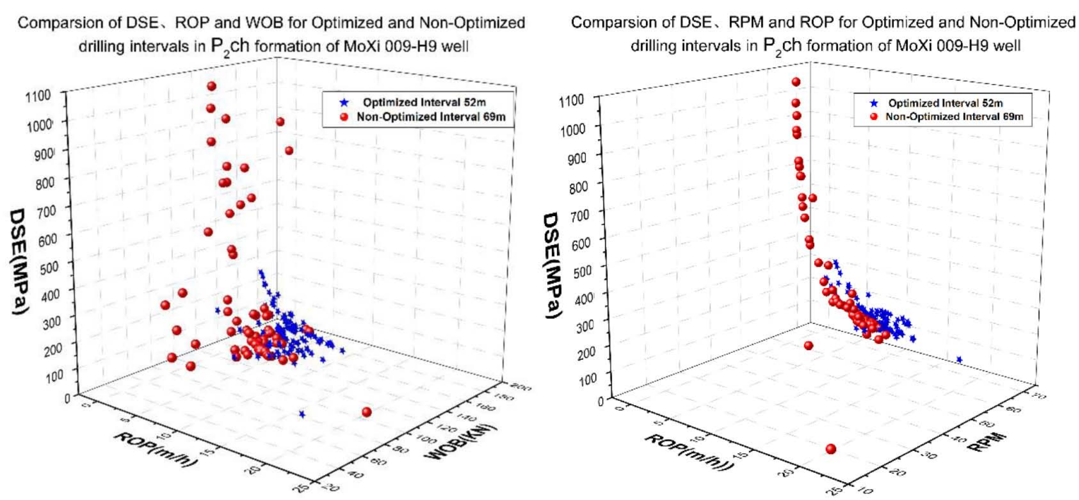


Figure 19—Drilling improvemnts in P_2ch formation

Conclusion

IADS is an effective, convenient, and smart tool for ROP enhancement through monitoring bit working performance. The system modules and the built-in models are able to automatically identify the limiters such as lithology change and vibrations etc., and provide the recommendations for drillers in real-time. The field pilots have received impressive drilling performance improvements by comparison with the conventional drilling practice. According to the field pilot feedback, the overwhelming ROP may induce critical vibration sacrificing bit life, and waste of input energy. The effective recommendations provided by IADS are able to mitigate the downhole vibrations, and achieve the optimum correlation between ROP and energy input. Meanwhile, the estimate of downhole vibrations through surface data was validated by comparing with downhole memory sub.

References

1. Fred E. Dupriest William L. Koederitz Maximizing Drill Rates with Real-Time Surveillance of Mechanical Specific Energy. Paper SPE/IADC 92194 presented at the SPE/IADC Drilling Conference, Amsterdam, 23-25 Februrary 2005.
2. M.Cui, M.C.Sun, et al. Maximizing Drilling Performance with Real-Time Surveillance System Based on Parameters Optimization Algorithm. *Advances in Petroleum Exploration and Development*, Volume **8**, May 2014, pp. 15–24.
3. J. Dunlop, R. Lsangulov, et al. Increased Rate of Penetration through Automation. Paper IADC/SPE 139897 presented at the SPE/IADC Drilling Conference, Amsterdam, 1-3 March, 2011.
4. T. Richard, E. Detournay, M.Fear, et al. Influence of bit-rock interaction on stick-slip vibrations of PDC bits. Paper SPE 77616 presented at the SPE Drilling Conference, San Antonio, 29 September 2002.