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Maximizing Drilling Performance With Real-Time Surveillance System Based on Parameters Optimization Algorithm

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Abstract

With deeper exploration and development of hydrocarbon reservoirs, a novel drilling parameters optimization algorithm, named as Navigation Optimization (NAVO) based on mechanical specific energy (MSE) theory, was investigated to continually improve the rate of penetration (ROP) and drilling performance. From the perspectives of rock mechanics and conservation of energy, the relationship among drilling parameters, ROP and MSE has been derived from comprehensive analysis of optimized drilling mechanism. Based on the R.Teale MSE model, the specific energy concept, considering the effect of hydraulics energy on rock breaking efficiency, is further extended based on the hydro-mechanical specific energy (HMSE). With the principle of maximum ROP and minimum HMSE, drilling parameter recommendation model was established, and a real-time drilling optimization system was developed and named as DrillNAV. The DrillNAV system could monitor all dynamic drilling parameters during drilling operations and feed back the advisory for drillers in real time. A pilot test showed the use of DrillNAV provided about 35% higher ROP with identification of downhole vibrations. It showed that NAVO algorithm can optimize drilling parameters in real time, which can be used to drilling performance evaluation and rock breaking analysis so as to raise the ROP and reduce drilling cost.

Key words: Navigation optimization; Hydro-mechanical specific energy; Drilling parameter recommendation; DrillNAV system

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INTRODUCTION

With increasingly deeper drilling targets, limiters, such as high abrasiveness of formation, misunderstanding bit behaviors and unknown real-time well hole situation, have hindered the improvement of drilling performance in China. Based on official statistics, the number of deep wells, whose depth is above 4,000 m, is 832 for the China National Petroleum Corporation (CNPC) in 2013. Hence, various types of cutting-edge technologies have been applied to deep wells; however, the monopolization of technologies brings out the high costs in drilling. The novel technologies and costs are dual challenges for improving the rate of penetration (ROP) during drilling process. Thus, it is essential to establish a simple and safety drilling scheme with low cost in China.

Conventionally, ROP is used as the index to evaluate the drilling performance. However, it cannot excavate the maximum potential drilling performance in condition of current drilling technologies and geology, and the high ROP generally leads to over wearing of bits. Meanwhile, the concept of Hydro-Mechanical Specific Energy (HMSE) is proposed to quantitatively evaluate drilling performance cooperating mechanical energy with hydraulic energy. The HMSE value is the total energy required to excavate a unit volume of rock. It is generally used as a method to identify the limiters affecting the drilling efficiency without real-time judgments or guidance of the reasonability of drilling parameters. Therefore, a novel optimization algorithm, named as Navigation Optimization (NAVO) for real-time drilling performance optimization, is established to achieve the maximum ROP with minimum HMSE during drilling process. The optimization algorithm is applied to a real-time surveillance system automatically guiding rig personnel for drilling efficiency. The success of pilot test proved that the optimization algorithm is feasible for improving drilling performance, providing useful insights into the judgment of the reasonability of drilling parameters.

1. ANALYSIS OF OPTIMIZAION MECHANISM

During drilling process, weight is applied to the bit leading to the cutters continuously cut into rock. Additionally, bit rotations result in the cutters lateral movement with rock breaking. Generally, depth of cut per revolution is presented as ROP divides RPM, thus better estimating relationship between input energy and drilling performance. In Figure 1, region I shows the depth of cut is inadequate, resulting in the waste of energy and lower ROP due to the lower WOB. As shown in the plot, the input energy and ROP initially do not keep the linear relationship. In region II, along with the increasing WOB, the depth of cutting into rock is adequate. Therefore, the bit performance becomes stable, keeping the linear relationship with the input energy. The energy is exclusively utilized for rock breaking in this region. In region III, input energy is continuously applied, but the depth of cut per RPM is not linearly increasing with the input energy, indicating more energy lost. The onset of limiters constrains the energy utilization, and the depth of cut per RPM stops responding linearly with increasing energy at this point. This point is referred as a founder one, where the bit efficiency is close to the highest level with the current system.

The third region starts at the founder point where the limiters constraining energy transfer. The main limiters include lithology changes, bit balling, bottom-hole balling, vibration, and so on. In certain hydraulics conditions, the cuttings are gradually accumulated at the bottom. Because of effect of pressure difference and inadequate bottom cleanup, lots of cuttings are attached to bit and bottom, causing bit balling and bottom hole balling. The balling hinders the efficient transmission of energy, resulting in the lower ROP. Subsequently, the increasing WOB leads to the buckled drillstring. While the whirl happens, the drillstring rotation contacts the hole wall, and the bit motion is not along the center of hole. As the WOB reaches a certain level, the stick slip will happen. However, whirl and stick slip commonly occur overlap in situ drilling condition[1]. Additionally, the formation compressive strength and abrasiveness alternates with the depth of formation also lead to decreasing of drilling performance. Therefore, Figure 2 shows the process that redesigns and optimizes parameters remove the limiters, keeping the bit efficiency accessing to region II all the time.

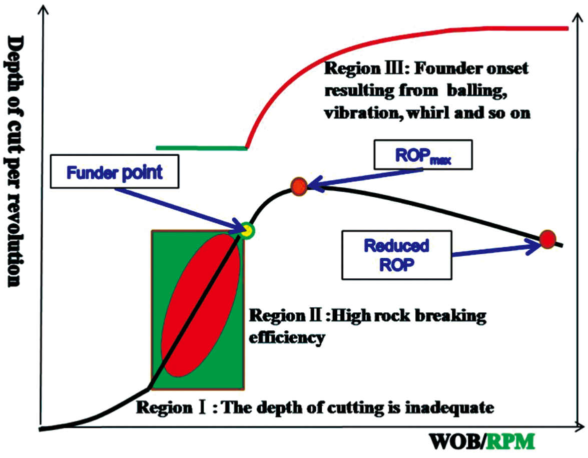


Figure 1
The Rock Breaking Mechanism Analysis Among the Drilling Parameters, ROP and Energy

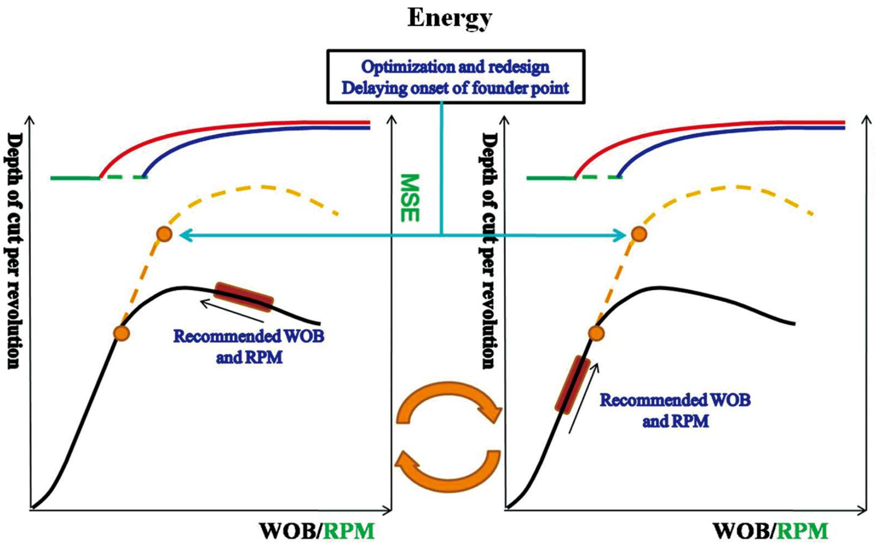


Figure 2
The Measures Taken in the Process of Drilling Performance Improvement

2. PARAMETERS OPTIMIZATION MODEL

Parameters optimization model is aimed to gain maximum ROP with improving drilling performance. During drilling process, the energy is applied to excavate the formation with the same CCS, and drillability is a constant value. However, bit limiters or non-bit limiters generally result in increasing HMSE, with negative effect on drilling performance in the condition of the same lithology. Therefore, limiters identification, relying on real-time drilling parameters, is essential to diagnose the in situ bit stall. Meanwhile, the energy required to destroy a given volume of rock should change with lithology. Thus, rock breaking energy should be quantitatively reevaluated in the new formation. Real-time HMSE data is processed by change-point identification algorithm judging the changes of drilling efficiency to provide the advisories for drillers. The algorithm divides a heterogeneous data series into a sequence of homogeneous segments, thereby making sure accuracy of parameters adjustment.

A Bayesian on-line change-point identification algorithm is applied to process real-time HMSE data obeying a Gaussian distribution[2] $x_i \sim N(\mu,\sigma^2)$. Gaussian distribution, whose density function is given by

$$f(x)=\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{1}$$

where μ is expectation; σ standard deviation; x HMSE data points. In a certain HMSE data sequence $\{x_1, x_2, \cdots, x_n\}$, change-point divides the sequence into two parts shown as follows:

$$\begin{aligned} &x_i \sim N(\mu_a,\sigma_a^2)\ldots(i=1,2,\ldots,k)\\ &x_i \sim N(\mu_b,\sigma_b^2)\ldots(i=k+1,\ldots,n)\end{aligned} \tag{2}$$

where μ_a, σ_a and μ_b, σ_b are scale parameters of the half of the sequence, respectively.

Change-point identification algorithm analyzes the probability of the change-point on the each point of HMSE data sequence, which is given by (see Figure 3)

$$p(k|x)=\iint p(k|x,\mu_a,\mu_b)\,d\mu_a\,d\mu_b \tag{3}$$

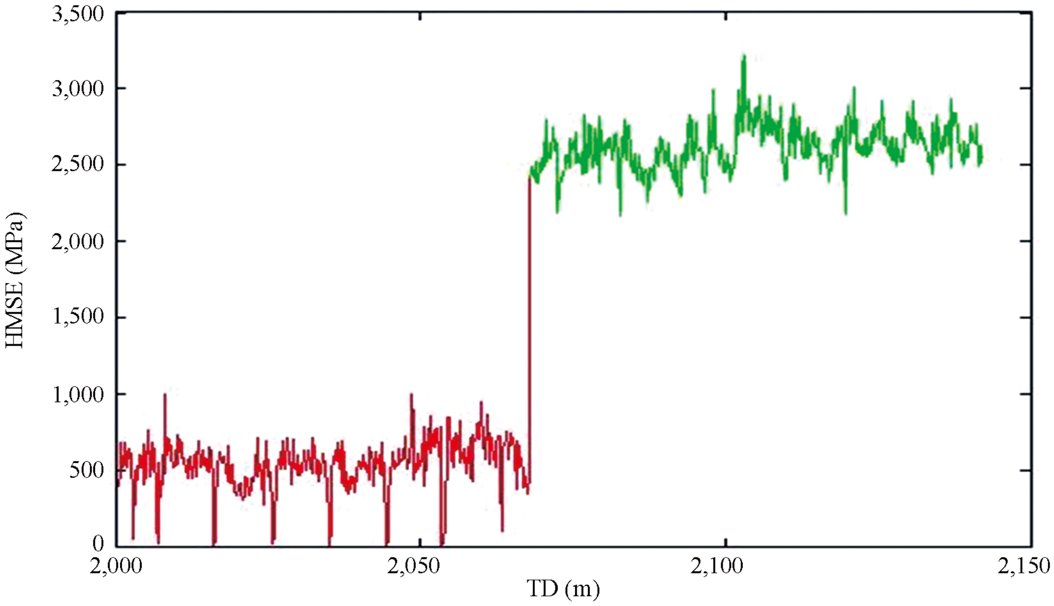


Figure 3
The Calculation Results of Bayesian On-Line Change-Point Identification Algorithm

According to PDC bit breaking mechanism[3], depth of cut per revolution increases linearly with the WOB. Depth of cut per revolution can be presented as ROP divides RPM. Additionally, the drilling performance has a direct relationship with WOB, RPM, torque, flow rate, and so forth. Moreover, rock breaking mechanism concludes that torque is directly proportional to the WOB. Thus, the real-time functions of depth-of-cut versus WOB and WOB vs. torque are significant to analyze the bit behaviors in the current drilling conditions so as to recommend the optimized parameters. The functions are presented through the least squares fit, which is given by[4-5]

$$c_j=\frac{\left(f(x),\varphi_j(x)\right)}{\left(\varphi_j(x),\varphi_j(x)\right)}=\frac{\sum_{i=0}^{m}\omega_i f(x_i)\varphi_j(x_i)}{\sum_{i=0}^{m}\omega_i\varphi_j^2(x_j)} \tag{4}$$

$$s^*(x)=\sum_{j=0}^{n}c_j\varphi_j(x_j)$$

where $f(x)$ = Depth of cut, mm or WOB, kN;

x_i = WOB, kN or torque, kN-m;

x = Independent variable;

$s^*(x)$ = Fitting function of depth of cut vs. WOB or function of WOB vs. torque;

ω_i = Constant, generally ω = 1;

c_j = Coefficient of function;

$\varphi_j(x_j)$ = Interpolation cardinal functions.

MSE is defined as the amount of energy required per unit volume of rock drilled. Not only hydro-power of bit can clean up the cuttings avoiding repeat breaking, but also jet impact force could directly break rock with low strength of rock[6]. Therefore, mechanical energy should be cooperated with hydraulic energy so as to establish HMSE model. The comprehensive effect of WOB, torque and hydraulics energy on rock breaking is demonstrated in HMSE model.

A simplified version of the specific energy is presented as follows:

$$\mathrm{SE} \approx \frac{\mathrm{SE}_{\mathrm{input}}}{\text{Output ROP}} = \frac{W_{\mathrm{total}}}{V_{\mathrm{ROP}}} \tag{5}$$

where SE_{input} = Input energy, MPa.

W_{total} = Total work per unit time of the various forces which applied to rock, J

V_{ROP} = Per volume rock drilled, m^3

Thus, HMSE is expressed as follows:

$$\mathrm{HMSE} = \frac{W_{\mathrm{WOB}} + W_{\mathrm{RPM}} + W_{HJ}}{V_{\mathrm{ROP}}} \tag{6}$$

where W_{WOB} = The work of WOB applied to excavated rock, J.

$$W_{\mathrm{WOB}} = WOB \cdot ROP \tag{7}$$

W_{RPM}= The work of torque applied to excavated rock, J

$$W_{\mathrm{RPM}} = 2\pi \cdot RPM \cdot T \tag{8}$$

W_{HJ}= the work of hydraulic power was performing per volume rock drilled.

$$W_{HJ} = \eta \cdot H_P = \eta \cdot \Delta P_b \cdot Q \tag{9}$$

According to equation of energy conservation, for the certain diameter of nozzle and flow, differential pressure of bit is expressed as follows:

$$\Delta P_b = \frac{\rho_d Q^2}{2000 C^2 A_0^2} \tag{10}$$

where C = nozzle flow factor, dimensionless, and generally $C < 0$.

Per volume rock drilled is expressed as

$$V_{\mathrm{ROP}} = A_B \cdot \mathrm{ROP} \tag{11}$$

Therefore, the Equations 7, 8, 9, and 11 are substituted into Equation 6, HMSE Equation is given by

$$\mathrm{HMSE} = \frac{\mathrm{WOB_e}}{A_B} + \frac{120\pi \mathrm{RPM} \cdot T}{A_B \mathrm{ROP}} + \frac{\eta \Delta P_b Q}{A_B \mathrm{ROP}} \ \mathrm{V} \tag{12}$$

The parameters optimization algorithm strives to achieve the minimum MSE and maximum ROP by optimizing parameters. Thus, the objective function of optimization drilling efficiency is established based on Equation 10 and Equation 4, which is given by:

$$\mathrm{HMSE}_{opt} = \frac{4 \times \mathrm{WOB}}{\pi d_B^2} + \frac{480 \times \mathrm{RPM} \times \left(c_0 \mathrm{WOB} + c_1\right)}{d_B^2 \times \mathrm{ROP}_{opt}} + \frac{\eta \Delta P_b Q}{A_B \mathrm{ROP}} \tag{13}$$

where HMSE_{opt} = Optimum hydro-mechanical specific energy, MPa;

d_B = Bit diameter, mm;

c_0, c_1 = Coefficients of fitting function of WOB and torque.

η = dummy factor for energy reduction, it related with the ratio of nozzle jet velocity to turn fluid velocity, nozzle diameter and the distance of the nozzle from the formation.

Offline simulation results of optimization algorithm of parameters are demonstrated in Figure 4. Comprehensively considering mechanical characteristics for top drive, drill-string and BHA, limits are imposed upon the drilling process for a variety of reasons. In Figure 4, the blue dashed lines boundaries of WOB and RPM are the top drive limits based on performance parameters. Red solid lines represent top drive limits with mud motor within the BHA. Optimized ROP contour of 5 m/hr is shown as blue solid line. MSE optimized contours of 1,500 MPa and 2,500 MPa intersecting with ROP contour. Therefore, the optimized direction is the green crossing point of HMSE contour and ROP contour.

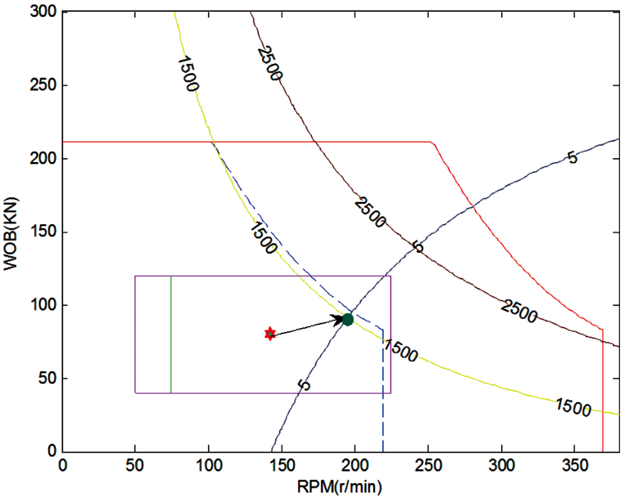


Figure 4
Offline Recommendation Simulations From Parameters Optimization Algorithm

3. SYSTEM ARCHITECTURE

Based on NAVO algorithm and hydraulic-MSE theory, the DrillNAV real-time drilling surveillance and advisory system was developed to allow the real-time computation of recommendations of drilling parameters and delivery to the rig personnel. The system real-time utilizes the data from compound logging, measuring instrument and sensors etc in order to enhance the drilling performance and yield a common drilling optimization method. The characteristics of the DrillNAV system are full parameters, save energy and enhance ROP. The full parameters display the ability to analyze how to effectively integrate the engineering parameters with hydraulics parameters. Saving energy embodies that the DrillNAV system provides the strategy as to improve the drilling efficiency avoiding energy lost. ROP improvement hints that mining the potential of ROP leading to maximize ROP is the objective for the DrillNAV system. The Figure 5 displays the overall architecture of the DrillNAV system.

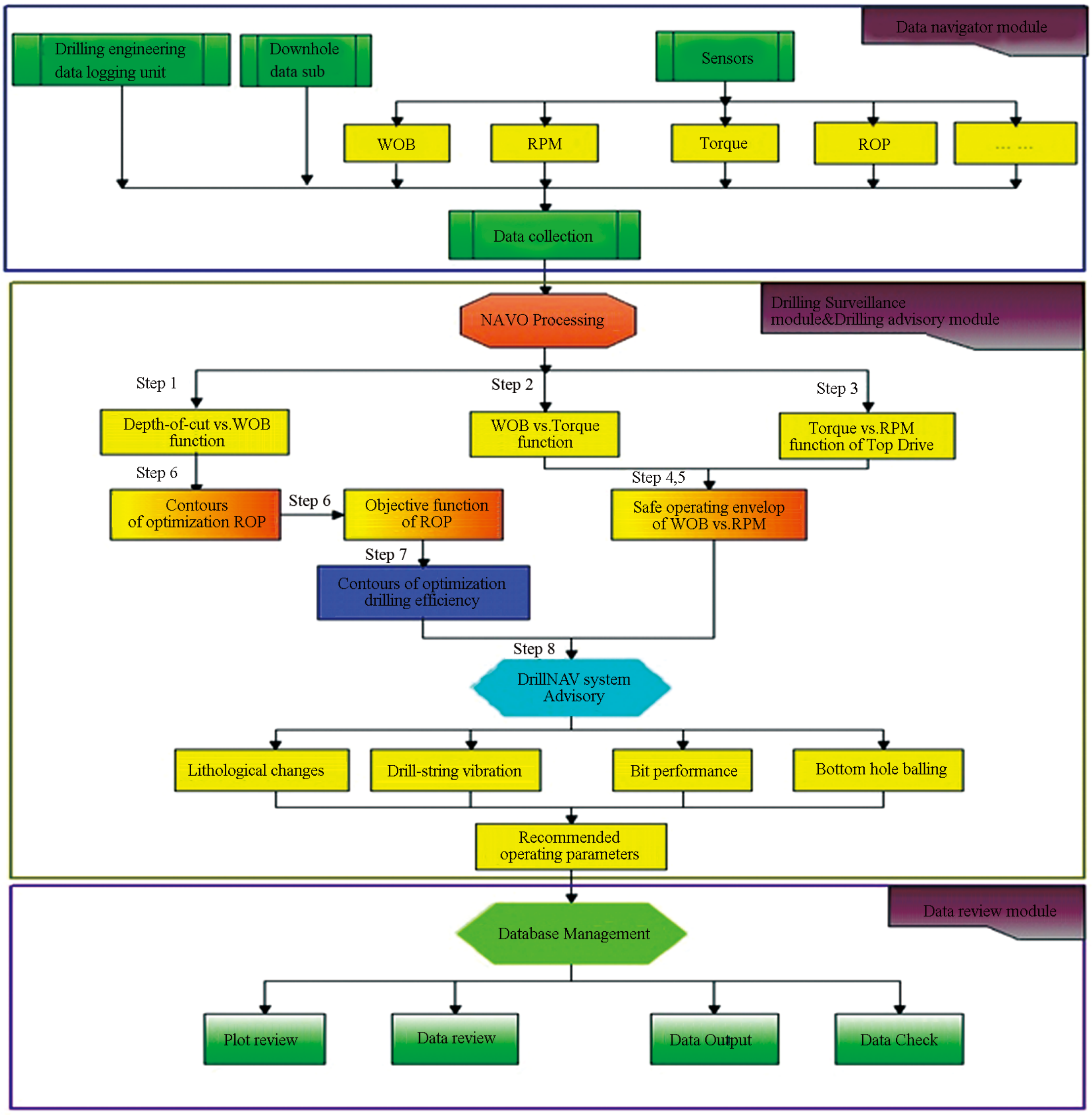


Figure 5
The DrillNAV System Architecture Used to Real-Time Surveillance and Recommendation

The components of the architecture and their respective roles are shown as follows:

(a) Data Navigator Module

Providing real-time data service for drilling surveillance and optimization. The module can acquire source data, code the data into WITS format and storage them into database in real time. Additionally, the module can automatically detect information regarding DrillNAV communication and operational status. Meanwhile, diagnostic information is provided in the form of indicator. A continuous blink for indicator shows the system is to communicate with data provider. If the data service interrupt with certain error, the blink will be disappear.

(b) Drilling Surveillance Module

Using advanced algorithms, real-time drilling parameters, and other set rig/well data to calculate HMSE, as well as other drilling parameters. These parameters are then displayed on driller interface in the form of curves to analyze drilling process in real time. Timely HMSE value is one of the primary value-added benefits Drilling Surveillance module provides. HMSE is one of the optimization criteria used to evaluate drilling efficiency. Data trends show the driller with changes in formation and other drilling conditions.

(c) Drilling Advisory Module

It is complementary for the Drilling Surveillance module. The module monitors the drilling process, and makes recommendations in the form of setpoints. The objective is to enhance the drilling efficiency in real time. According to change point detector algorithms, the streaming data is processed to periodically make optimized recommendations.

(d) History Review Module

It enables the comparison of offset wells with previously acquired depth-based drilling parameters. Based on the algorithms, the users could evaluate the drilling performance for analogous wells. Additionally, the module provides the analysis ability to evaluate the formation characteristics, including UCS, CCS, pore pressure, fracture pressure, and so on.

This ensures representative and quality data while the well is being drilled to continually optimize drilling performance and ROP, making time and cost saving possible.

4. FIELD TEST CASES

4.1 Optimization Guidelines

The basic principle of optimizing the hydraulic parameters is to guarantee the effect of hole cleaning, followed by the consideration of supporting role of hydraulic energy in rock breaking. It was found that under the condition of the current mud flow rate, hydraulic energy is involved in rock breaking directly, and the flow rate meets the need to ensure carrying cuttings.

Figure 6 described detailed instruction on applying real-time HMSE. In a reasonable scope, WOB should be firstly adjusted, followed by rotation speed and flow rate adjustment. Basic idea is that WOB should experience a process from decrease to increase, combined with rotation speed and flow rate from decrease to increase. As long as the obtained HMSE is equal or close to the HMSE baseline (CCS of rock) after adjusting drilling parameters, it shows that the optimized drilling parameters could meet the needs of optimization; if not, drilling parameters should be restored to the original values. Principally, the change range of WOB, rotation speed and flow rate should not be more than 20%.

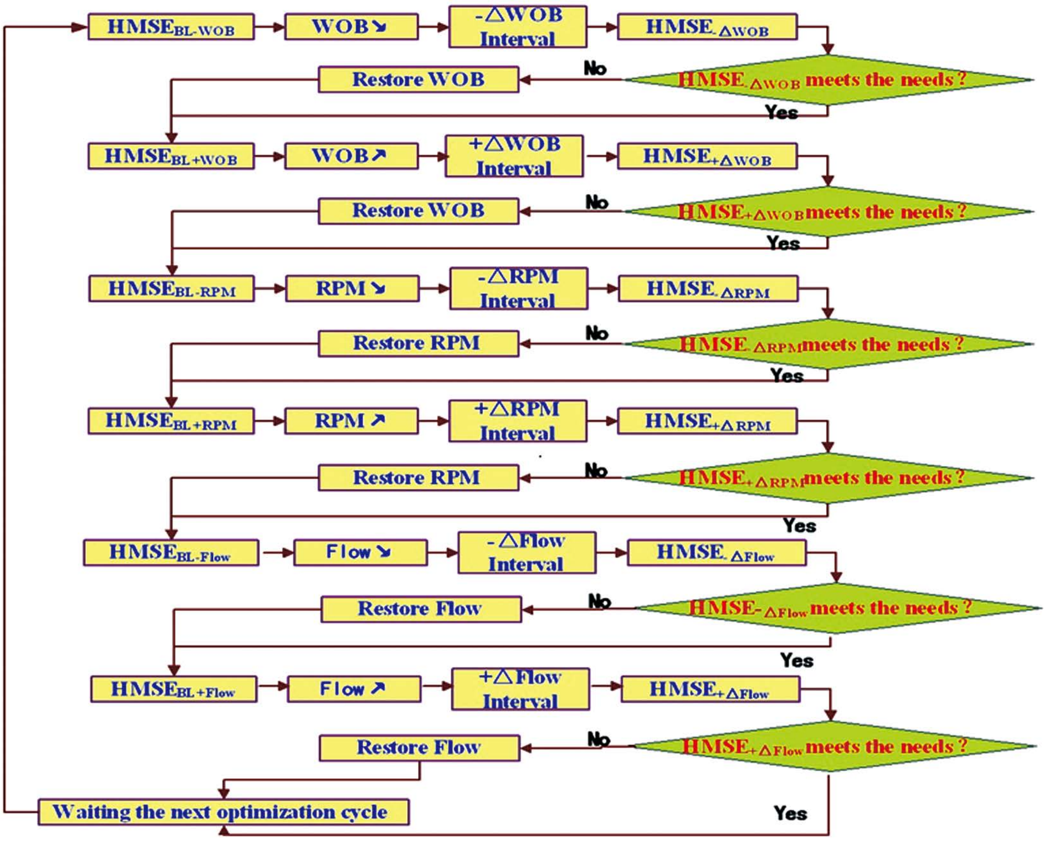


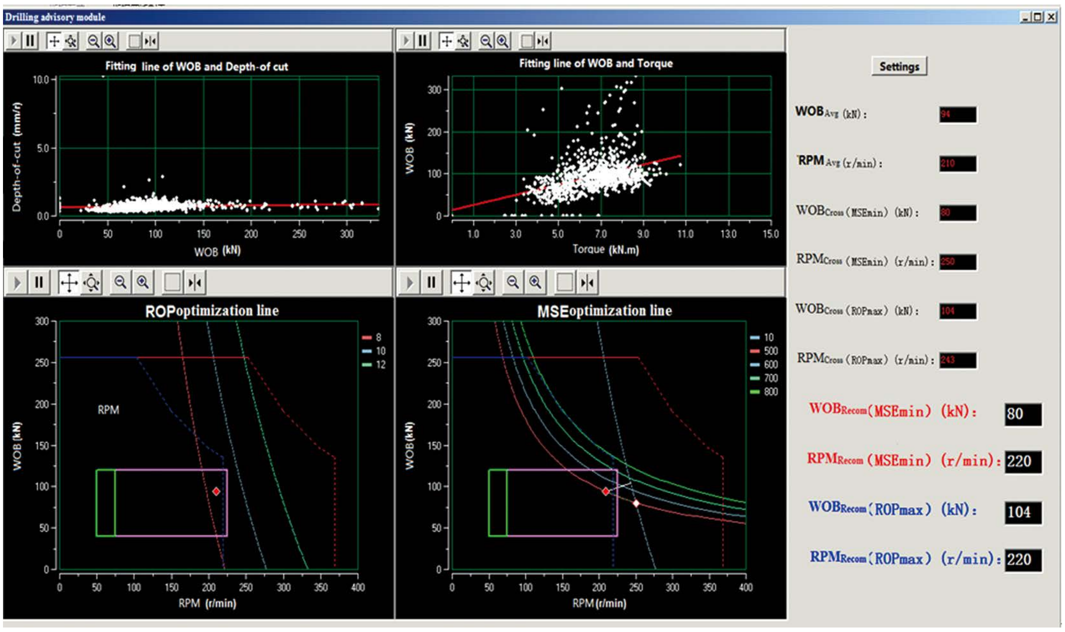
Figure 6
The Structured Method for Drilling Performance Optimization Strategy

4.2 Cases Analysis

DrillNAV system was configured for a recent in situ trial in the Yumen oil filed, China, where drilling efficiency improvement, bit balling resolving and lithologies identification were taken. The formation in the test interval is mainly mudstone and sandstone in an interbeded abrasive formation. A full string of 5-inch drillpipe, an 8-1/2-inch PDC bit and water base mud were used in the test interval.

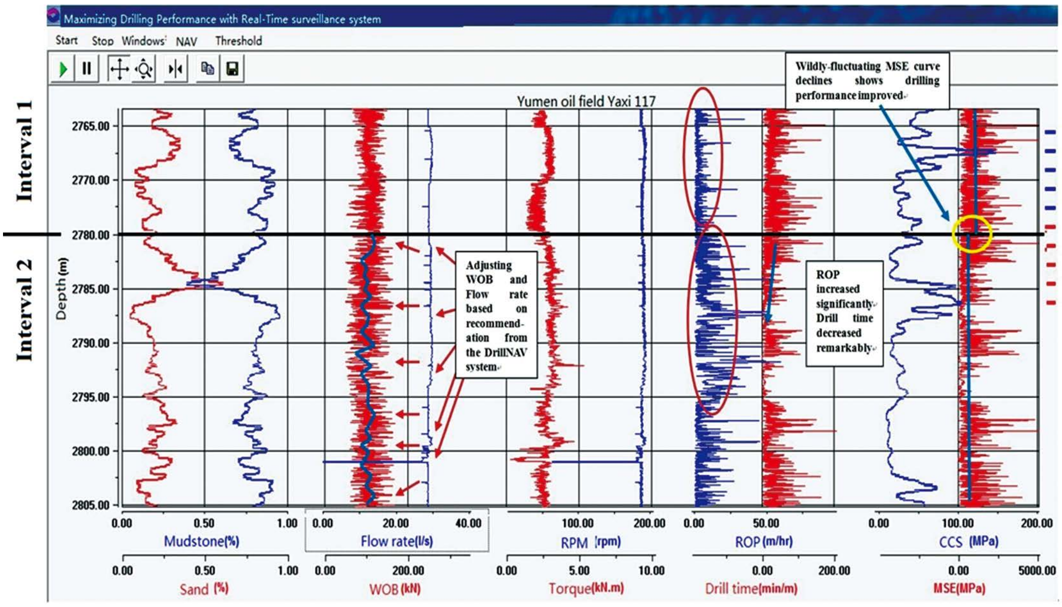
Based on experiences of offset, the design parameters were 60 RPM and 80 - 120 KN WOB in order to achieve the best drilling efficiency and balance bit wear enhancing life.

Figure 8 shows the DrillNAV system corresponding to the different operating practices applied in each section. Above the interval 1 of black line, the driller followed conventional methods to set parameters values. However, under the interval 2 of black line, the driller was instructed to follow the DrillNAV recommendations. Figure 7 sheds the recommendation results from DrillNAV system. Comparing two intervals, the MSE tendency of optimized section 2 is obviously lower than the section 1, and a higher level of ROP has been achieved, though the formation in section 2 is deep with higher rock strength.



WOBAvg (kN): 94
RPMAvg (r/min): 210
WOBCross (MSEmin) (kN): 80
RPMCross (MSEmin) (r/min): 250
WOBCross (ROPmax) (kN): 104
RPMCross (ROPmax) (r/min): 243
WOBRecom (MSEmin) (kN): 80
RPMRecom (MSEmin) (r/min): 220
WOBRecom (ROPmax) (kN): 104
RPMRecom (ROPmax) (r/min): 220

Figure 7
The Recommendation Results From the Drilling Advisory Module



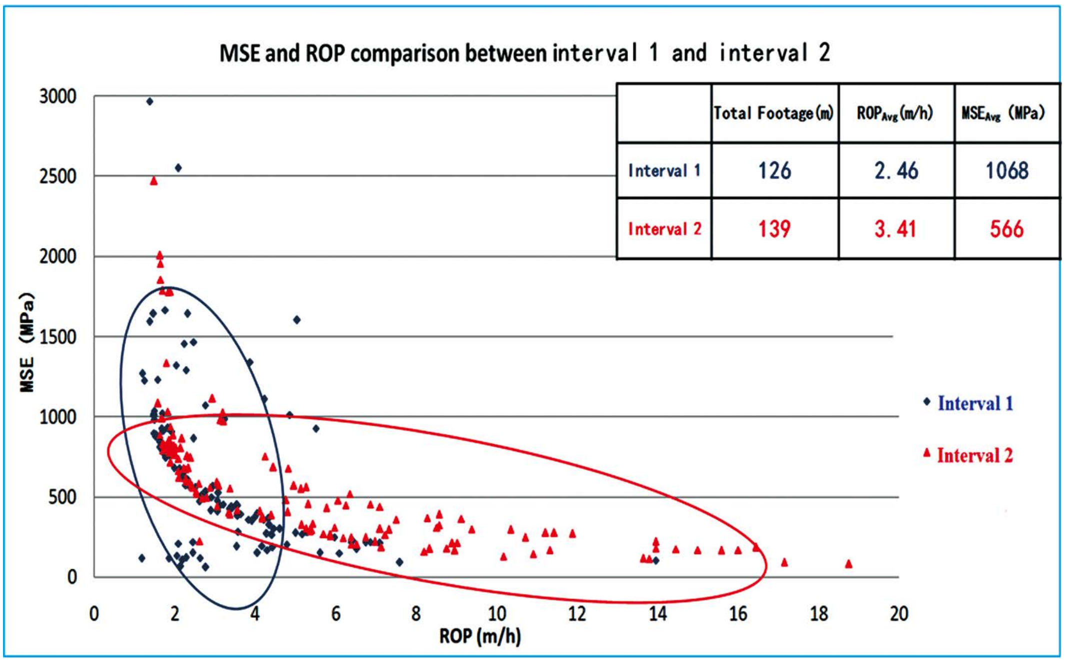
Wildly-fluctuating MSE curve declines shows drilling performance improved.

Adjusting WOB and Flow rate based on recommendation from the DrillNAV system.

ROP increased significantly. Drill time decreased remarkably.

Figure 8
The Comparison of Drilling Performances Between the Intervals

Additional figure can more highlight optimization effect. Figure 9 provides the joint MSE-ROP values distribution for each interval. The blue color data points are derived from the interval without the DrillNAV system application, and the red color data points from the optimized section 2. The distribution of bulk of MSE data is below, and the ROP higher in interval 2 compared with the interval 1. The average MSE value of 1,068 MPa in interval 1 is 47% higher than the average value of 566 MPa in interval 2. Meanwhile, the average ROP value of 3.41 m/h in interval 2 is 27% higher than the average value of 2.46 m/h in interval 1. According to comparison, the improved drilling performance has been achieved with DrillNAV application.

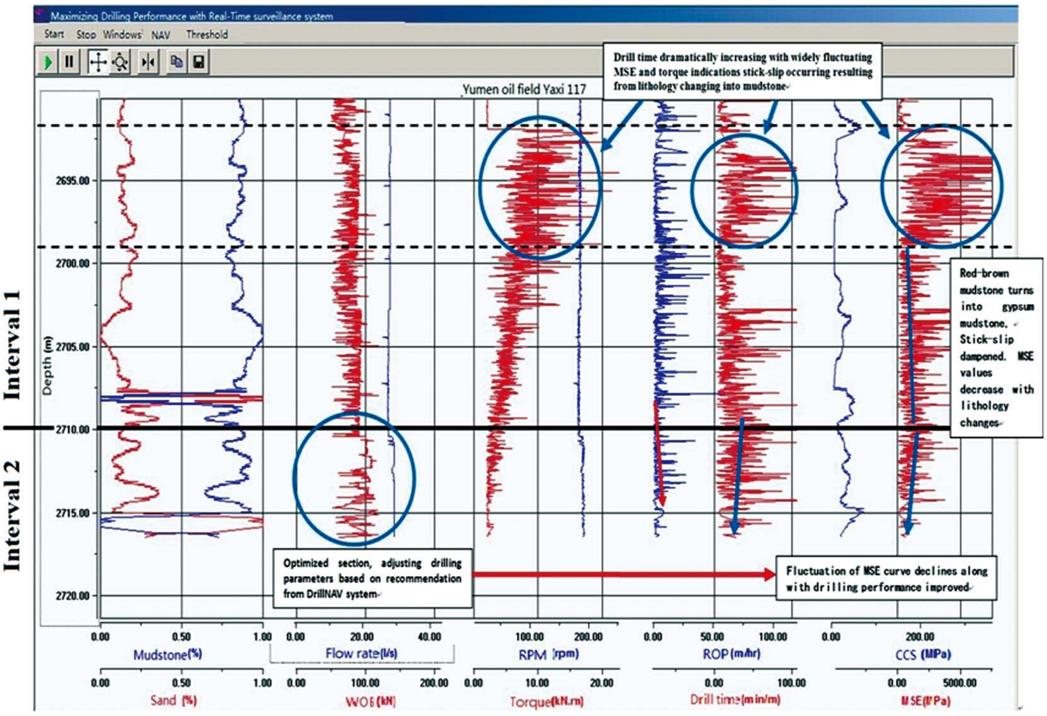


	Total Footage(m)	ROP_{Avg}(m/h)	MSE_{Avg} (MPa)
Interval 1	126	2.46	1068
Interval 2	139	3.41	566

Figure 9
The Distribution Comparison of ROP and MSE for Test Intervals

Generally, vibrational founder is very common, even in rocks of moderate compressive strength. When the bit vibrates it loses cutting efficiency, and the MSE value clearly shows the resulting increase in energy consumption. Figure 10 is a typical example to diagnose vibrational founder due to stick slip. Stick slip was persistent and commonly occurred in mudstone while the hydraulic horsepower was not enough, and resulting in the rotational speed of bit is unstable. A dramatic change of the rotational speed at the bit, leading to the torque applied at the end of the string, reaches a critical fluctuation level exciting the drill string vibration. In Figure 10, torsional vibration occurs in 8-1/2″ interval 1 of test well. The MSE value is plotted in the right hand track. At the beginning of this interval, the initial MSE value was around 300 MPa; torque around 3 KN-m; WOB around 80 KN; rotational speed around 190 RPM (including mud motor); the flow rate 28 l/s. The MSE plot showed the most of energy was used for breaking rock at the beginning of interval. The vibrational founder was onset at 2,693 m; the MSE value increased dramatically; ROP decreased obviously. Meanwhile, the torque value increased from around 3 KN-m to 10 KN-m with frequently spikes of up to 15KN-m. According to changes of parameters, DrillNAV correctly diagnosed high energy loss due to moderate stick slip resulting from lithology changing into mudstone (See Figure 11). However, the driller did not take any measures to dampen vibration without utilization of DrillNAV system. Stick slip consumed amount of energy resulting in declining of drilling efficiency. Until 2,700 m, the lithology changed from mudstone to gypsum mudstone, leading to relieve of stick slip (See Figure 10). According to surveillance, MSE curve decreased dramatically, indicating the drilling performance improved along with lithology changes (See Figure 12). The DrillNAV system was applied after 2,710 m, according to recommended results. The flow rate increased from 28 l/s to 30 l/s, and WOB from 80 KN to 100 KN to guarantee enough depth of cut and hole cleaning. From MSE curve and torque curve, the increase in hydraulics enabled the cutting structure to remain clean at much lower energy lose resolving stick slip, and both sands and mudstone were drilled uniformly at more than 5 m/h for the next 150 m.

Real-time surveillance of MSE and automatic parameters recommendation has enabled the relationship among compressive strength of rock, engineering parameters, hydraulics, mechanical energy and ROP. The ability to quantify the founder point has also begun to distinguish bits which were previously thought to have better behaviors during drilling process for rig personnel.



Drill time dramatically increasing with widely fluctuating MSE and torque indications stick-slip occurring resulting from lithology changing into mudstone

Red-brown mudstone turns into gypsum mudstone. Stick-slip dampened. MSE values decrease with lithology changes

Optimized section, adjusting drilling parameters based on recommendation from DrillNAV system

Fluctuation of MSE curve declines along with drilling performance improved

Figure 10
Stick Slip Occurring With Lithology Changing Into Mudstone at 2,693 m

Figure 11
The Lithology Changes Into Mudstone at 2,693 m

Figure 12
The Lithology Changes From Mudstone to Gypsum Mudstone at 2,699 m

CONCLUSION

(1) Based on the MSE model formulated by Teale, considering jet impact force for effect of breaking rock, HMSE model was established enabling the drilling performance evaluation to be more accurate.

(2) A novel optimization algorithm has been modeled for achieving the maximum ROP and minimum HMSE, and guiding drillers with the automatic recommendation drilling parameters. This can further expend the range of application to HMSE drilling optimization. In addition, a drilling optimization system named as DrillNAV was developed real-time utilized during drilling process.

(3) The pilot proved that the drilling process, optimized by justifying potential design changes and identifying the limiters in the current system, achieves the better drilling performance compared with the offset wells. The surveillance system based on HMSE can be used as an all-purpose tool for well design, real-time optimization and post analysis. If the drillers are trained for utilizing the system to identify the limiters, the system will be a useful tool for improving drilling rate and reducing drilling cost in China.

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NOMENCLATURE

HMSE = Hydro-Mechanical Specific Energy, MPa
SE = Specific Energy, MPa
ROP = Rate of penetration, m/hr
WOB = Weight on Bit, kN
RPM = Bit rotating speed, Revolutions Per Minute
CCS = Confined Compressive Strenth, MPa
BHA = Bottom Hole Assembly
NAVO = Navigation Optimization Algorithm

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