Research on PDC drilling parameter optimization based on dynamic drilling strategy

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Abstract: Drilling parameters optimization is very important for practical engineering drilling, and the rationality of the selected optimization mode directly affects the accuracy of the parameters obtained. The maximum bit performance curve which can reflect the relationship between the depth reached by a single bit and the maximum drilling speed is introduced, which provides a method basis for preparing multi-bit drilling program and dynamic drilling strategy. Through the dynamic drilling strategy, the optimal bit operation combination is provided, so as to achieve the minimum drilling cost in a long drilling interval. The study shows that dynamic drilling strategy as a new drilling optimization method has high cost-effectiveness. The calculation example shows that the design method saves 18% of the cost compared with the drilling optimization method, and 40% of the cost compared with the drilling process without optimization treatment.

Key words: Drilling parameter optimization, maximum bit performance curve, dynamic drilling strategy, drilling cost.

1. Introduction

The optimization of drilling parameters is to obtain the relevant data parameters through drilling process, and through certain processing and processing, get the data parameters that can be used in another new wells design [1]. These new parameters can be used for comparison of measures and prediction of indicators to ensure economic optimum in drilling process. The core question of whether the obtained parameters are reasonable is whether the selected mathematical method conforms to the objective law of drilling.

There have been some studies on Optimization of drilling parameters. According to the structural characteristics of mid-deep well in Daqing Oilfield and the influence degree of various random factors on drilling speed, Sha Llinxiu has established a multivariate stochastic drilling rate equation. Through the study of real-time optimization method of drilling parameters, Lan kai [3] has established a set of theoretical system for real-time optimization of drilling, and has developed a set of "real-time monitoring and optimization decision system of drilling parameters", which takes comprehensive mud logging and field operation parameters as the main data sources. Warren T M [4] took the relative ratio of various rocks and standard rock samples as the index of rock samples, takes into account the effects of drilling pressure, drilling rate, rock strength, bit type and bit size, and obtained the drilling rate equation applicable to soft to medium hard formations. Finally, the modified drilling speed equation is obtained which is capable for the situation that drilling fluid cannot completely clean the bottom hole. Zhao Shijun [5] et al. aimed at optimizing bit usage and judging the best time to start drilling, made cost curve per meter according to drilling parameters and increment of cost per meter with drilling, judged bit usage on the basis of which to determine the best time to start drilling. These studies are only applied to the bit drilling process, not considering the whole drilling process, and have considerable limitations. The maximum bit performance curve is introduced as the method basis of multi-bit drilling program and dynamic drilling strategy. The optimal combination of bit operation is selected by dynamic drilling strategy, and the drilling cost is minimized.

2. Optimum Bit Performance (MBP) Curve

The maximum performance curve of drill bit is derived from optimization theory, but this new concept has shown strong practicability. In engineering sense, the MBP curve shows the relationship between the length of the footage of a single bit and the maximum penetration rate. The optimal bit performance curve reflects the shortest bit rotation time, the specific footage length or the maximum possible footage. From this, it can be seen that it is feasible to use the optimal bit performance curve to express the optimization of drilling parameters, showing the necessary and single basic relationship between each

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other. This curve presents the most effective bit control program in a particular rock.

Each point on the mathematical model of MBP curve represents the unique solution of the following optimization model:

Minimum drilling time of bit:

$$t_b(W, N, \omega, A_f) = MIN; \quad (1)$$

The maximum footage a bit may achieve:

$$F = t_b R(W, N, \omega, K, ...)\, dt = Const \quad (2)$$

Within the following constraints:

$$\begin{aligned} W_0 \leqslant W \leqslant W_{\max} \\ N_{\min} \leqslant N \leqslant N_{\max} \end{aligned} \quad (3)$$

Constraints (3) represent torque limit (small drilling equipment), temperature limit (diamond bit and PDC bit), or mechanical strength (maximum bit pressure) and rotary drive limit (maximum bit rate). Formulas (1), (2) and (3) are all the cognitions of bit (mathematical model) derived from field data, laboratory tests and drilling theory. Then, all these perceptions are combined to determine the optimal bit performance curve. Field drilling technicians can easily use the curve to formulate the optimal drilling strategy.

The optimal bit performance curve of PDC bits is shown in Figure 1. The maximum drilling speed increases with the increase of footage length, which means that some worn PDC bits can drill faster than new bits. This unexpected performance is due to the temperature limit of the wear surface.

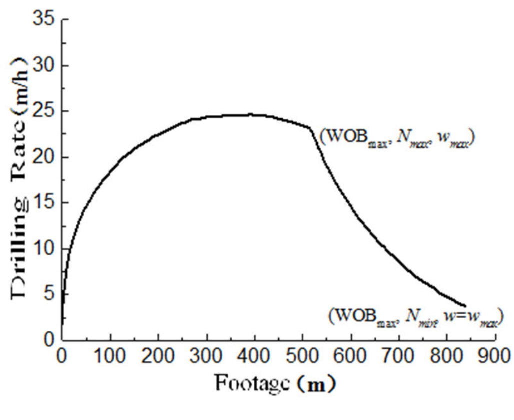

Figure 1 optimal performance curve of PDC bit

3. Optimization of drilling program

In formulating drilling bit schemes, drilling engineers need to complete the following tasks: (1) selecting bit types; (2) determining drilling parameters (W, N); (3) estimating the number of bits required. Traditionally, the above three points can be achieved by roughly estimating the bit performance according to the advice of the bit manufacturer and personal experience. However, in order to optimize the drilling program, it is necessary to try to select the continuous bit stroke combination and use the concept of minimum drilling cost, which is defined as follows:

$$C = \sum_{n=1}^{N_b} (C_{b_n} + C_R t_{t_n} + C_R t_{b_n}) = MIN \quad (4)$$

Limitations:

$$D_i - D_t = \sum_{n=1}^{N_b} F_n \quad (5)$$

In the formula: N_b is the total number of bits used; C_{bn} is the price of the nth bit, yuan; C_R is the operating cost of the drill, yuan; t_{tn} is the operating time of the nth bit ,h; t_{bn} is the life of the nth bit, h; F_n is the footage of the nth bit, m; D_i is the initial well depth, m; D_t is the total well depth, m。

In order to optimize the scheme, it is necessary to use PDC bit drilling model to calculate bit life t_{bn} and footage depth F_n, and to obtain the minimum value of formula (4) by optimization method.

3.1 Drilling-by-Drilling Optimization Method

As for drilling-by-drilling optimization, it is a conventional method for drilling parameter optimization. When each item in its hypothesis (4) has a minimum value, the total value will be minimized, namely

$$C_{F_n} = \frac{C_{b_n} + C_R(t_{t_n} + t_{b_n})}{F_n} = MIN \quad (6)$$

Formula (6) is the drilling cost formula per unit footage. This means that the drilling cost per unit footage of continuous bit stroke is the lowest and the total drilling cost is likely to be the lowest. However, in theory, this is not in line with the actual situation.

The optimal bit performance curve provides a simple method for optimizing the travel of a single bit. Formula (7) can be arranged as follows:

$$C_{F_n} = \frac{\frac{C_b}{C_{R_n}} + t_{t_n}}{F_n} + \frac{1}{\bar{R}} \quad (7)$$

Only when

$$C_{F_n} = \frac{\frac{C_b}{C_{R_n}} + t_{t_n}}{F_n} + \frac{1}{[\bar{R}]_{\max}} = MIN \quad (8)$$

It can reach its minimum value.

In the formula: $\bar{R}$ is the average drilling rate, m/h; $[\bar{R}]_{\max}$ is the optimum bit performance curve.

Obviously, the second half of the formula is the reciprocal of the optimal bit performance curve. Figures 2 and 3 show the chart analysis of the method. Figure 2 shows the minimum cost per meter of a conventional cone bit.

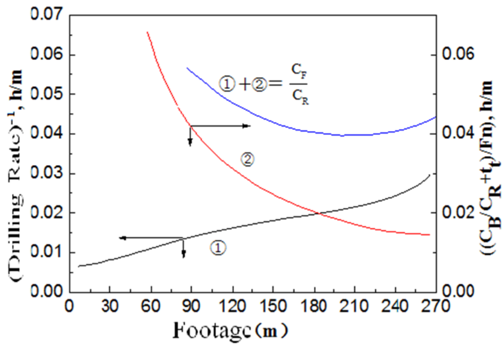

Figure 2 Conventional drilling optimization using MBP curve (cone bit)

The optimum bit-by-bit travel of all cone bits can minimize the drilling cost of each well, which is demonstrated in Figure 2. Relevant research shows that the cost saved by reducing the number of bits is usually less than the cost increased by lengthening the bit stroke, which is consistent with the steeper U-shaped minimum value in the cost curve of the footage per meter in this figure.

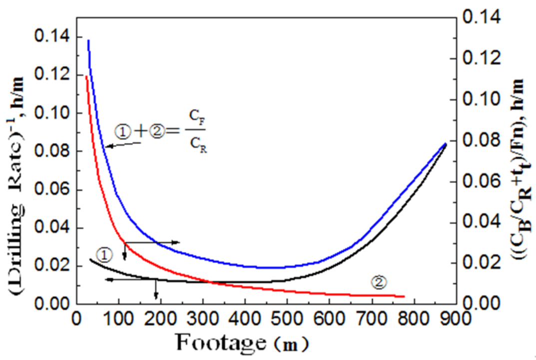

Figure 3 Conventional drilling optimization using MBP curve (PDC bit)

Figure 3 is the cost curve of PDC bit per meter. In a large numerical range, the U-shaped bottom moves smoothly, and the length of the footage has little effect on it. Therefore, the drilling cost obtained from drilling-by-drilling optimization is likely to be much higher than the actual minimum value in equation (4).

3.2 Dynamic Drilling Strategy

Dynamic drilling strategy is the design method of multi-bit drilling scheme. In multi-bit drilling scheme, the number of bits, the length of bit footage and drilling parameters are optimized simultaneously to obtain the lowest drilling cost of long interval. Usually, this typical section refers to the drilling section (surface, middle and productive drilling) from the casing support ring down to the set depth of the next casing. By summing up, the lowest cost drilling schemes for these sections will yield the lowest drilling cost for the whole well.

From the point of view of mathematical model, the optimal drilling strategy can solve the optimization problems described in formula (4) and formula (5). Operational research principles provide numerical methods and dynamic programming for solving such problems. The drilling operation is considered as a multi-stage decision-making process in which the number of stages (bit stroke) is unknown. In each PDC bit stroke, the bit control is determined (W, N, t_b, F) to minimize the drilling cost of the entire section specified in equation (4). By using the optimal bit performance curve, the multi-variable problem can be simplified to a simple proposition (F_1, F_2, ... F_n) of the optimal travel distribution of a continuous bit. Based on the principle of optimality in dynamic programming, a recursive formula is derived, through which the optimal distribution of bit stroke can be obtained. The distribution shows the optimum number of bits and the length of drilling footage. By using MBP curve, the length of drilling footage coincides with the corresponding bit control operation, and gives a complete and optimized drilling strategy.

The recursive formula of dynamic drilling strategy is as follows:

$$MIN[C(D_n)] = C_R MIN\{[C_b / C_R + t_t(D_n) + \frac{F}{[R]_{\max}}] + MIN[\sum_{j=1}^{n-1} C(D_i)]\} \quad (9)$$

In which,

$$F = F_n \exp[a_2 (D_n - D_i)]$$
$$n = 1,2,\ldots,\frac{D_t - D_i}{\Delta D} \quad (10)$$

In the formula, a_2 are the index of rock drill ability and well depth, and F_n is the record of the depth that a bit may drill from the well depth D_n.

For the assumed bit footage, it needs to be calculated and accumulated repeatedly to minimize the drilling cost of the bit footage. By using the optimum bit performance curve, the following results can be obtained:

$$C(D_n) = C_b + t_t(D_n) + [t_b(F)]_{\min} + MIN[\sum_{j=1}^{n-1} C(D_j)] \quad (11)$$

Based on Optimization theory, formula (11) is equivalent to the following expression (repeated calculation and accumulation):

$$C(D_n) = MIN\{C_b + t_t(D_n) + [t_b(F)]_{\min} + MIN[\sum_{j=1}^{n-1} C(D_j)]\} \quad (12)$$

Formula (12) constitutes the optimization method of dynamic drilling strategy, which can be solved by computer programming in the process of parameter iteration. When the final step length $(D_t - D_i)/\Delta D$ and $D_n = D_i$ are determined, the value calculated by the above formula is equal to the lowest drilling cost of drilling depth from D_i to D_t. Formula (12) gives the optimum travel distribution and the number of PDC bits used.

4. Comparison of Optimum Design Methods

Based on the actual engineering parameter data, the relevant data are processed by MATLAB software, and the dynamic drilling strategy optimization, drilling-by-drilling optimization and field application are compared to evaluate the technical effect and economic potential of the dynamic drilling strategy. For the 2400m part of medium-hard and medium-abrasive strata with site strata

1200-2400m and 3600m-4800m:the average drilling speed is 9.14 m/s, the maximum drilling pressure is 178 kN, the average speed is 115 rpm/min, the compaction index A=0.0002, the drilling rig cost is 1600 yuan/h and the bit cost is 96,000 yuan. The data used for calculating the optimal bit performance curve include: drill ability constant is 0.29cm/kN, speed index a_1 is 0.8, maximum bit pressure is 178kN, minimum speed 40/min, maximum speed 250/min, bit diameter 21.6cm, cutting tooth inclination α is 15°, thermal conductivity of rock is 0.086Btu/h.°C.cm^2, side inclination angle β is 5°, the diameter d_c of cutting surface is 1.32 cm, the cutting tooth temperature is 350℃, and the thermal response function f is 9.545 x 10-4.

The influence of drilling depth on drill ability constants can be expressed as follows:

$$K(D) = K(D_i)\exp[a_2(D_i - D)] \quad (13)$$

Drilling time is calculated as follows:

$$t_t = 0.001D \quad (14)$$

Relevant data are collated, as shown in Table 1.

Table 1 Comparison of design method for drilling parameters optimum

method	bit #	Drilling depth （m）	Footage （m）	Cost yuan/m	Drilling speed （m/h）	bit wear	Cumulative drilling time （h）	Cumulative cost（yuan）
Dynamic Drilling Strategy Optimization	1	4206	589	44.09	19.66	1.0	27.9	260302
	2	4602	396	64.57	12.37	1.0	59.88	535843
	3	4907	304.8	84.72	9.6	1.0	91.55	**813962**
Drilling- by-drilling optimization	1	4176	518	43.95	23.38	1.0	22.15	245235
	2	4572	396	62.83	13.38	1.0	51.73	512861
	3	4877	304.8	82.68	10.42	1.0	80.9	783957
	4	4907	30.48	651.97	7.41	1.0	85.06	**993534**
Field application	1	4136	478	57.20	9.02	1.0	52.94	293835
	2	4527	391	72.03	8.8	1.0	97.38	596775
	3	4768	241	109.53	6.77	1.0	133.02	880764
	4	4884	116.4	228.35	3.33	1.0	167.97	1167945
	5	4907	23.2	7068	0.15	1.0	320.50	**1331554**

Table 1 shows that compared with field application, dynamic drilling optimization strategy can reduce the cost by about 40%, drill-by-drill optimization can reduce the cost by 25%, and the number of bits required decreases in turn. Compared with drill-by-drill optimization, the cost of dynamic drilling strategy is reduced by 18%. Therefore, compared with traditional drilling optimization methods, dynamic drilling strategy has obvious advantages in reducing drilling costs.

5. Optimal Contrast Based on Footage Scale

The number of bits needed in the drilling process mainly depends on the depth of the well, and the number of bits has a very important impact on the reduction of drilling costs. By introducing the relevant variable of footage rate, the footage rate is the ratio of the maximum footage of the bit to the depth of the well. Then, if the footage ratio is 1, theoretically one bit is needed for drilling; if the value is 0.2, it means that at least five bits are needed. The advantage of introducing this variable is that it combines the depth of the well with the number of bits in the same order of magnitude, providing a method for comparing different bits.

The research results are summarized and the change curves shown in Fig. 4 are drawn. The curve is a sensitivity analysis of the influence of bit scheme selection on cost. As can be seen from the figure, when the well depth is within the range of one PDC bit, the cost can be saved up to 40%. However, with the increase of well depth, the extent of cost savings will gradually decrease. The cost-effectiveness of dynamic drilling strategy is very sensitive to the change of well depth. With the change of feed rate, the cost savings fluctuate between zero and maximum. In summary, in order to avoid the possibility of potential cost savings, dynamic drilling strategy should be used to optimize the drilling process, rather than drilling-by-drilling optimization. Therefore, compared with the optimization method of drilling by drilling, the dynamic drilling strategy can save drilling cost to the greatest extent.

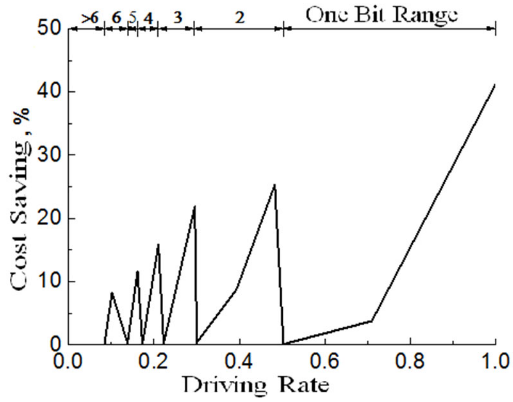

Figure 4 Sensitivity Analysis of Bit Scheme Selection on Cost

The above research shows that dynamic drilling strategy is very suitable for optimizing the drilling process of PDC bit. Especially in the hard and medium formations of long-distance drilling, the potential function of this optimization method makes the performance of PDC bit surpass almost all other bits. PDC bits can produce long-distance footage, the number of drilling intervals required is small, and at least one PDC bit will only wear locally.

6. Conclusion

PDC bit drilling model is used to verify and prove the feasibility and accuracy of dynamic drilling strategy optimization theory. The maximum bit performance curve which can reflect the relationship between the depth reached by a single bit and the maximum drilling speed is introduced, which provides a method basis for preparing multi-bit drilling program and dynamic drilling strategy. Dynamic drilling strategy provides the optimal bit operation combination, so as to achieve the minimum drilling cost in a longer drilling interval. The following conclusions are drawn:

(1) Dynamic drilling strategy as a new drilling optimization method has high cost-effectiveness. By comparing the actual cases, the cost of this design method is 18% less than that of the traditional drilling optimization method, and 40% less than that of the drilling process without optimization treatment. Moreover, the dynamic drilling strategy can be easily simplified to meet the field application.

(2) The optimal dynamic drilling strategy is especially suitable for the steady advancement of bit technology, that is, for stronger, durable and more expensive PDC bits, and for offshore areas where drilling costs are very high.

(3) When drilling parameters are optimized, the use of PDC bits in drilling process can be greatly reduced through the perfect combination of the optimal bit performance curve (MBP) and dynamic drilling strategy, and the ultimate goal of cost-saving and efficient drilling can be achieved.

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