Controllable drilling parameter optimization for roller cone and polycrystalline diamond bits

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Abstract

Oil well drilling data from 23 oil wells in northern Iraq are analyzed and optimized controllable drilling parameters are found. The most widely used Bourgoyne and Young (BY) penetration rate model have been chosen for roller cone bits, and parameters were extracted to adjust for other bit types. In this regard, the collected data from real drilling operation have initially been averaged in short clusters based on changes in both lithology and bottom hole assemblies. The averaging was performed to overcome the issues related to noisy data negative effect and the lithological homogeneity assumption. Second, the Dmitriy Belozarov modifications for polycrystalline diamond bits compacts have been utilized to correct the model to the bit weight. The drilling formulas were used to calculate other required parameters for the BYM. Third, threshold weight for each cluster was determined through the relationship between bit weight and depth instead of the usual Drill of Test. Fourth, coefficients of the BYM were calculated for each cluster using multilinear regression. Fifth, a new model was developed to find the optimum drill string rotation based on changes in torque and bit diameter with depth. The above-developed approach has been implemented successfully on 23 oil wells field data to find optimum penetration rate, weight on bit and string rotation.

Keywords Bourgoyne and Young model · Clustering · Drilling · Multiple linear regression · Optimization

Introduction

Oil well drilling technique is the process of making a safe vertical or inclined cased hole (Rabia 2002). An experienced team of qualified personnel, drilling program, and powerful drilling rig are the main basic requirements to perform a drilling operation (Azar and Samuel 2007). Reduction in cost and/or time without compromising safety is key topics for optimized drilling performance. Optimization in drilling operations started with the first attempt to drill in 1900 (Eren and Ozbayoglu 2010). The process of optimization was slow in the beginning and became quicker with scientific and technological developments. Despite all advances, however, still, there are challenges in understanding the overall drilling operation process. These challenges pushed researchers to continue their work to identify and model

drilling processes and to study further the main parameters that affect oil well operations (Darley 1969; Khodja et al. 2010). From 1920 to date, many parameters have been studied in different models. Bourgoyne and Young (BY) was one of these models used in optimizing the controllable drilling parameters. This model was conducted in 1974 for eight parameters in one equation for optimal rate of penetration (ROP) in roller cone bits (Bourgoyne et al. 1986; Bourgoyne and Young 1974; Caenn et al. 2011; Eckel 1968; Eren and Ozbayoglu 2010). Other researchers used charts, relationship between a set of parameters in their works (Bingham 1965; Gatlin 1960; Maurer 1962; Warren 1987). Computer programs were developed in different areas to find optimal weight on bit (WOB) and rotation per minute (RPM) (Barragan et al. 1997; Bourgoyne and Young 1974; Coelho et al. 2005; Galle and Woods 1963). Lummus, for example, studied the optimization process through analysis of mud hydraulic properties (Lummus 1971). Different mathematical models implemented to optimize WOB, RPM, and bit hydraulics (Bourgoyne et al. 1986; Graham and Muench 1959; Speer 1958). Borehole cleaning, lifting capacity, bit types, and hydraulic parameters have been studied by many

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researchers in seeking more optimized operations (Garnier and Van Lingen 1959; Maurer 1962; Naganawa 2012). Many researchers focused on regression analysis and empirical correlation in their works to reduce the drilling time (Duklet and Bates 1980).

Despite all advances still, the need for more optimized operational is crucial. Recently, the BYM has been studied by Eren Tuna (Eren and Ozbayoglu 2010). He studied the real-time optimization of ROP using regression analysis to find the BYM coefficients. Tuna used the data of two wells to optimize the controllable parameters of a third well. In fact, many other researchers considered the BYM as one of the best drilling optimization models because it is based on a statistical analysis of past drilling parameters, like WOB and RPM. The BYM has been successfully implemented in different locations on roller cone bits (Elahifar et al. 2012; Eren and Ozbayoglu 2011; Irawan and Anwar 2014; Miyora et al. 2015). Nevertheless, this model needs substantial adjustments before using it on other types of drilling bits like fixed cutter bits. Recently, Christensen, Inc. and Shell Oil Co. used the corrected BYM for polycrystalline diamond (PDC) bits to optimize the penetration rate (Duklet and Bates 1980). In almost all drilling operations, the operator uses different types of drilling bits (roller cone and fixed cutter bits) in the same well. Thus, using the BYM with corrections expands the applicability of the model. In this paper, field data from the Bazian oil block in northern Iraq are used with the original model in the upper intervals where the roller cone bits are used. A corrected BYM was used in other intervals where the PDC bits were used in the drilling operations. The drilled sections were partitioned into 20 clusters based on bottom hole assemblies (BHA) and the lithology changes. Roller cone bits were mainly used in drilling the upper clusters, while, PDC bits were used in the other clusters. Optimized WOB, RPM, and ROP parameters were predicted for future operations in the same geological setting.

Methodology

In this study, the drilling operations of 23 oil wells were monitored in three different oil blocks in northern Iraq. The three oil blocks were Taq Taq, Bazian, and Miran. The Bn-1 oil well located in the Bazian block was selected to be a key well for this study. This oil well has been monitored closely to collect all the operational data starting from the civil works to the site restoration. Appendix Table 7 shows a part of the field data from the mud logging unit (MLU) that were collected and used in this study. A set of data for each meter from the surface to the final depth at 3715 m has been collected from different sources. The MLU data

were selected because it was the most continuous and complete data set.

The collected data of WOB, RPM, ROP, and torque were averaged in short intervals of 10 m to reduce the effects of noisy data and homogeneity assumptions. Then, the collected data have been divided into 20 clusters based on lithology and bottom hole assembly (BHA) changes as shown in Fig. 1. The needed parameters for the BYM were determined from standard drilling formula (DF) calculations. Parameters such as equivalent circulation density (ECD), bottom hole pressure (BHP), Reynold number, pore pressure gradient (Pg) and annular pressure were calculated through the DF. The BYM contains the effect of eight variables of drillability, normal and abnormal compaction, pressure difference, bit weight, string rotation, bit wear, and bit hydraulics. The eight effective operational parameters (x_1 – x_8) of the BYM were calculated through specific equations (Bourgoyne and Young 1974), as in Appendix Table 8. Multiple linear regression techniques were used to compute optimum coefficients (a_1 – a_8), as Appendix Table 6. Based on the relationship between RPM, bit diameter and torque with depth, a new model was derived to calculate optimum RPM. The new model is a function of only two parameters (Torque and Bit diameter). The main methodology steps are illustrated in Fig. 1.

Well profile

The drilling operation in Bn-1 oil well was spudded on October 2009 and finished in 256 days after penetrating the Triassic rocks at a total depth of 3715 m (Korea National Oil Corporation, KNOC 2009). The final casing setting depth was with the 7-in. liner at 3640 m (Korean National Oil Corporation, KNOC 2009). Figure 2 shows penetrated formations, casing size and setting depth for all the drilled sections from the surface with 30-in. conductor pipe ended to the 6-in. casing for and Open Hole Section at 3715 m. The geological stratigraphy showed alternation of different geological formations from the surface to the final depth (Darwesh 2014). Figure 3 shows 20 different geological formations starting from Eocene–Pila Spi formation to Triassic–Kura Chine formation. The actual drilling time spent on all the operating activities was more than the planned time due to drilling problems and shortage in the offset data (Darwesh 2014).

The surface section is characterized by hard, highly fractured and abrasive formations which cause excessive vibrations of the drill string and a total loss in the drilling fluid. Swelling and packing off were the problems in the intermediate section. Problems of tight spots and bridges were encountered also in this section. The production and liner

Fig. 1 Methodology flowchart

section showed a good drillability but with frequent loss of circulation and problems of fishing and sidetracking.

The rate of penetration (ROP) model

The BYM (1974) is a linear relationship between the penetration rate and a set of eight effective parameters x_1 – x_8 . This model was based on the statistical synthesis of the collected data from the previously drilled wells. This model considers the following eight effects:

- Formation strength
- Formation depth
- Formation compaction
- The pressure differential across the bottom of the hole
- Bit diameter and weight on bit
- Rotary speed
- Bit wear
- Bit hydraulics

First, the model was introduced for roller cone bits, as shown in Eq. 1 (Adam et al. 1991).

$$\frac{\partial f}{\partial t} = e^{\left(a_1 + \sum_{j=2}^8 a_j x_j\right)} \quad (1)$$

where $\frac{\partial f}{\partial t}$ is the rate of penetration (ft./h), a_j are the coefficients of the model and x_j the eight drilling parameters and explained below.

Effect of formation strength

This effect is represented by coefficient a_1 in the BYM and it is inversely proportional to the natural logarithm of the square of the drillability. The less value for this coefficient means less ROP. The coefficient also includes the effects of parameters not mathematically modeled, such as the effect of drilled cuttings in terms of size, type, quantity or any other effects (Bourgoyne and Young 1974). Other factors such as drilling fluid properties, solid content, the efficiency of the equipment/material, crew experience, and service companies' efficiency could be included under this function or as separate coefficients in future considerations. Equation 2 defines the formation of strength related effects with the same units of ROP.

$$f_1 = e^{a_1} \quad (2)$$

Fig. 2 Drilled and cased sections for Bn-1 oil well. Nonlinear depth scale used

where f_1 is the rate of penetration (ft./h) and the a_1 is a dimensionless coefficient for the formation strength.

Effect of formation compaction

Equations 3 and 4 define the effect of normal and abnormal formation compaction. These effects are represented by coefficients a_2 and a_3 .

$$f_2 = e^{a_2 x_2} \quad (3)$$

$$f_3 = e^{a_3 x_3} \quad (4)$$

where f_2 and f_3 are the rate of penetration (ft./h) and the a_2 and a_3 are dimensionless coefficients for the effect of normal and abnormal formation compaction

The normal compaction parameter x_2 assumes an exponential decrease in ROP with depth, while the abnormal compaction effect on penetration rate x_3 assumes an exponential increase in ROP with the pore pressure gradient (Bourgoyne and Young 1974). Equations 5 and 6 show the effect of formation compaction in BYM.

$$x_2 = 10000 - D \quad (5)$$

$$x_3 = D^{0.69}(g_p - 12.5) \quad (6)$$

where g_p the pore pressure gradient in units of ppg, D is depth in ft. and the numbers 10,000 and 12.5 have been chosen to normalize the effect of depth and pore pressure.

Fig. 3 Geological stratigraphy and formations penetrated in Bn-1

Depth (m)	Age		Formation	Main Lithology	Casing Targets (m)				
1000	Cenozoic	Eocene	Pila Spi	Limestone				30" @33m	
			Gercus	Clay					
			Khurmala	Limestone					
		Paleocene- Eocene	Sinjar						
			Kolosh	Marl, Marly limestone					
			Aliji	Marl, Clay					
	Cretaceous	n- Maastric htian	Tanjero	Marly Limestone					13 3/8"@1050
			Shiranish	Limestone, Marly Limestone					
		Turonian	Kometan	Limestone					
		Hauterivian – Albian	Qamchuqa- Balambo	Limestone , Marly Limestone					
Valanginian- Albian			Lower Sarmord	Marly Limestone, Limestone					
		Jurassic	Chia Gara	Marly Limestone	9 5/8" @1839				
Barsaren	Limestone								
Naukalkan	Marly Limestone								
Sargalu- Alan	Claystone								
Mush-Batmah	Limestone								
3000	Triassic	Baluti	Sandstone	7" @3715					
		Kura chine	Limestone						
3715									
3800									

Open hole section

Effect of bottom hole pressure differential

Coefficient a_4 in Eq. 7 represents the effect of pressure differential on ROP. The penetration rate will reduce with the decrease in the bottom hole pressure difference. Whenever the pressure differential between mud hydrostatic pressure and the formation pressure is zero, this effect will be equal to 1 (Bourgoyne and Young 1974).

$$f_4 = e^{a_4 x_4} \quad (7)$$

$$x_4 = D(g_p - \text{ECD}) \quad (8)$$

where f_4 is the rate of penetration (ft./h) and the a_4 is a dimensionless coefficient for the effect of bottom hole pressure differential, ECD is equivalent circulating mud density at the bottom hole in units of ppg.

Effect of bit diameter and weight on bit, (w/d)

The bit weight and bit diameter are considered to have a direct effect on the ROP. The constant a_5 in Eq. 9 represents the effect of WOB and bit diameter on the penetration rate. The parameter x_5 assumes that the ROP is directly proportional to $\left(\frac{w}{d}\right)^{a_5}$ (Bourgoyne and Young 1974).

$$f_5 = e^{a_5 x_5} \quad (9)$$

$$x_5 = \ln \left[\frac{\left(\frac{w}{d}\right) - \left(\frac{w}{d}\right)_t}{4 - \left(\frac{w}{d}\right)_t} \right] \quad (10)$$

where f_5 is the rate of penetration (ft./h) and the a_5 is a dimensionless coefficient for the effect of Bit Diameter and Weight on Bit, w/d is the WOB per inch of bit diameter in

units of 1000 lb/in., (w/d) , is the threshold WOB per inch of bit diameter. The number 4 is the normalized weight on bit in units of 1000 lb per bit diameter in an inch.

Fix cutter bits like polycrystalline diamond bit (PDC) was used widely in the drilling of Bn-1 and many other wells. This type of bit showed high performance in drilling soft-shale formations. Adding some special design features in recent years made this type of bits more effective in drilling medium-to-hard formations also (Belozarov 2015).

The PDC bit breaks the rock through shearing, and they do not have any moving or rotating parts as in roller cone bits. PDC bits consist of many fixed blades that are integral with rotation as a single unit of the drilling string (Belozarov 2015). Figure 4 shows the main differences between the roller cone and PDC bits.

Adjustments were applied on the x_5 to suit PDC bits before running the regression analysis, and both bit weight and bit diameter were adjusted. Belozarov (2015) adjustments were selected to adjust the effect of bit weight parameter. Dmitriy Belozarov adjustments were based on the relationship between mechanical and critical weights on the PDC bit, as seen in Eqs. 11, 12 and 13 to find x_5 .

$$x_5 = \ln \left[\frac{C_r \cdot \left(\frac{w}{d} \right) - 0.942 \cdot \Delta P_b \left(\frac{d-1}{d} \right)}{\left(\frac{w}{d} \right)_c} \right] \quad (11)$$

$$x_5 = \ln \left[\frac{C_r \cdot \text{WOB}_a - 0.942 \cdot \Delta P_b \left(\frac{d-1}{d} \right)}{\text{WOB}_c} \right] \quad (12)$$

$$\Delta P_b = \frac{q^2 \cdot \rho}{12031 \cdot A_n^2} \quad (13)$$

where C_r is the dimensionless weight split between the 12¼" drill bit and 13½" under-reamer; in case of no under-reamer

it will equal to 1. $\text{WOB}_c = 800$ lbs/in. is the chosen weight to normalize WOB value for PDC bits. The coefficient 0.942 was high, probably due to hydraulic friction losses, and therefore, it was reduced by 0.02 in this paper. WOB_a is the measured weight on the surface in l bf. A_n is the nozzle total flow area in a square inch and q is the mud pump flow in units of mph.

The minimum needed WOB to start the drilling process (threshold weight) was found through the relationship between the ROP and the WOB as in Fig. 5. This force can be determined on-site by drill-off tests for each formation during the drilling operation by plotting the ROP as a function of WOB per bit diameter and then extrapolating back to a zero-drilling rate (Bourgoyne et al. 1986). In Fig. 5 before point (a) there is no record of ROP with the applied WOB, but then a linear relationship appears between the points (a, b and c). Subsequently, the relationship is nonlinear from (c) to the (d). After point (d), any increase in the WOB will not give an increase in the ROP (24). Thus, point (a) is the threshold value of that specific formation and drilling bit.

In this study, the threshold weight was determined through the plotted relationship between WOB and the depth in each cluster separately. Figure 6 shows the relationship between the applied weight and the depth in the first cluster (Pila Spi formation—Eocene). The minimum weight of 0.7

Fig. 5 Weight on bit and rate of penetration relationship (Ahmed et al. 2018)

Fig. 4 Main features of PDC and roller cone bits used in Bn-1 (Karadzhova 2014)

Fig. 6 Weight on bit versus depth for the first cluster (Pila Spi) formation

ton was recorded for the mentioned formation. Later, this weight was converted to (weight/drilling bit diameter) as shown in Table 1.

The same procedure was performed to determine other threshold weight for all other clusters.

Effect of rotary speed N

The effect of the rotary speed (N) described by the coefficient a_6 and the parameter x_6 . It is assumed that the ROP is directly proportional to the rotation speed of the bit. Based on the Dmitriy Belozarov model (Belozarov 2015),

the normalizing value to equalize the rotary speed function differs between roller cone bits and PDC bits. ROP usually increases linearly with the rotary speed at low values of rotary speed, but this effect will change at high rotation speeds into a nonlinear relationship (Bourgoyne and Young 1974). At higher values of rotary speed, the ROP will decrease due to an increase in drilled cutting and a decrease in lifting capacity (Warren 1987). This effect is modeled in Eqs. 14, 15 and 16 below for roller cone and PDC bits (Adam et al. 1991) (Belozarov 2015):

$$f_6 = e^{a_6 x_6} \quad (14)$$

Table 1 Bn-1 clustering intervals and threshold weight

Cluster no.	Lithology no	Formation	Interval (ft.)	Hole diameter (in.)	(w/d) _r (1000 lb/in.)	Clustering base
1	1	Pila Spi	32–450	26	0.0577	Geological Fm.
2	2	Gercus	450–808	Surface section	0.131	Geological Fm.
3	3	Khurmala	808–1082		0.585	Geological Fm.
4	4	Sinjar	1082–1444		0.681	Geological Fm.
5	5	Kolosh	1444–1496		0.592	Bit change
6			1496–1575		0.427	Bit change
7			1575–2326	17.5	0.257	Bit size change
8	6	Aliji	2326–3445	Intermediate section	0.20	Bit change
9			3445–3930		0.137	Bit change
10			3930–5489	12.25	0.196	Bit and Fm. change
11	7	Upper Shiranish	5489–6033	Production section	0.359	Bit change
12			6033–6375		0.433	Bit size change
13	8	Lower Shiranish	6375–6670	8.5	0.18	Bit change
14			6670–7477	Liner section	0.259	Geological Fm.
15	9	Kometan	7477–7795		0.376	Geological Fm.
16	10	Qamchuqa	7795–8179		0.047	Bit change
17			8179–10,253		0.047	Bit change
18			10,253–11,552		0.047	Bit change
19	11	Qamchuqa/Sarmord	11,552–11,926	6	0.067	Bit size change
20			11,926–12,480	Open hole	0.050	TVD

$$x_6 = \ln \left(\frac{N}{100} \right) \quad \text{For roller cone bits} \quad (15)$$

$$x_6 = \ln \left(\frac{N}{160} \right) \quad \text{For PDC bits} \quad (16)$$

where f_6 is the rate of penetration (ft./h), N =rotations per minute (RPM), numbers 100 and 160 are normalization factors for roller cone and PDC bits.

Effect of tooth wear

The coefficient a_7 represents the effect of tooth wear on penetration rate. ROP decreases with the increase in bit teeth wear. Reductions in ROP for tungsten carbide insert (TCI) roller cone bits and PDC bits are not as severe as for milled tooth (MT) roller bits (Gatlin 1960). During the use of TCI and PDC bits, the ROP does not vary significantly with tooth wear. Thus, the tooth wear exponent for TCI roller bits $a_7 x_7$ in Eq. 17 becomes zero and this means that $e^{a_7 x_7}$ becomes equal to 1 (Bourgoynne and Young 1974). In the drilling of Bn-1, the TCI and PDC were dominantly used below 500 m and the effect of tooth wear (h_f) has set to (1/8) as an alternative of zero. The value of 1/8 was selected to justify the worse dull case below the casing shoe, with a linear increase from zero to 8/8 to 1/8 (Belozarov 2015). The linear increase of wear in TCI and PDC bits is preferred compared to the nonlinear relation as in MT bits.

$$f_7 = e^{a_7 x_7} \quad (17)$$

$$x_7 = -h_f \quad (18)$$

where f_7 is the rate of penetration (ft./h), h_f is the fractional tooth height that has been worn away over 8.

Effect of bit hydraulics

The coefficient a_8 in Eq. 19 represents the coefficient for the effect of the bit hydraulics on ROP. The effect of the bit hydraulics x_8 assumes that the ROP is proportional to a Reynolds number or jet impact force (Bourgoynne et al. 1986).

$$f_8 = e^{a_8 x_8} \quad (19)$$

The Reynolds number gives the effect of the drilling bit jetting action at the bottom of the hole, which promotes better cleaning of bits teeth. Through Eqs. 20 and 21, this effect can be determined and be normalized to 2.0 hp/in. chosen for the hydraulic horsepower.

$$x_8 = \frac{Hp/A_b}{2} \quad (20)$$

$$PH = \frac{\Delta P_b/A_b}{1714} \quad (21)$$

where f_8 is the rate of penetration (ft./h), A_b =bit area square inch, ΔP_b =bit pressure drops [psi] and Hp =Hydraulic horsepower [hp].

The previous Eqs. 2–21 are used to calculate x_1 to x_8 , and the coefficients a_1 to a_8 from multiple regression and thereby the optimum WOB and RPM can be determined.

Clustering and threshold weight determination

Based on the BHA and lithology changes, the whole penetrated depth was partitioned into 20 clusters, as shown in Table 1. The total of 11 geological formations was recorded from the surface to the final depth. In the upperpart of the well, four geological formations have been drilled with the same bit but they are treated as individual clusters. In some geological formations, different drilling bits were used and each interval is treated as one cluster.

Instability problems such as shales swelling, cavings, tight spots, and eventual loss of circulations were encountered during the drilling operation (Darwesh 2014). These problems caused an increase in drilled cuttings and therefore increased pore pressure and annular density (Guo and Liu 2011). Equation 22 was used to calculate the ECD that was increased due to the weight of drill cuttings in the annulus (Skalle 2011). This equation takes into account the frictional loss due to the circulation of the drilling fluid (Aadnoy 2011; Lyons and Plisga 2011).

$$ECD = \frac{P_{an}}{0.052h} + M_w \quad (22)$$

where ECD is equivalent circulating density in units of ppg, P_{an} is Annulus frictional pressure loss in units of psi, h is depth in ft and M_w is mud weight in ppg.

A linear regression method which contains more than one variable is called a multiple regression (MLR) (Montgomery and Runger 2010). MLR was conducted for each cluster to calculate a_1 to a_8 for the BYM and the results attached and shown in Appendix Table 6. Based on the chosen rig, personal and bottom hole assemblies (BHA) selection, the optimum values WOB have been calculated using Eq. 23.

$$[w/d]_{opt} = \frac{a_5 H_1 \left(\frac{w}{d} \right)_m - \left(\frac{w}{d} \right)_t}{a_5 H_1 - a_6} \quad (23)$$

where a_5 and a_6 can be obtained from the regression analyses. Table 2 contains parameters of the bit wear model as described by (BY references), where $(w/d)_m$ is the maximum weight on bit diameter and H_1 , H_2 and H_3 are coefficients

Table 2 Tooth wears parameters recommended by Bourgoyne and Young (Bourgoyne et al. 1986)

Tooth wear parameters recommended by Bourgoyne and Young (8)				
Bit class	H_1	H_2	H_3	$(w/d)_m$
1-1 to 1-2	1.9	7.0	1.0	7.0
1-3 to 1-4	1.8	6.0	0.8	8.0
2-1 to 2-2	1.8	5.0	0.6	8.5
2 to 3	1.76	4.0	0.48	9.0
3 to 1	1.7	3.0	0.36	10.0
3 to 2	1.65	2.0	0.26	10.0
3 to 3	1.6	2.0	0.20	10.0
4 to 1	1.50	2.0	0.18	10.0
Insert	1.5	1	0.02	See Table 3 below

provided by the International Association of Drilling Contractors (IADC). All the results were in an acceptable range (Bourgoyne et al. 1986; Eren and Ozbayoglu 2010) between the recorded minimum and the maximum value of WOB. For example, the required values for the coefficients and variables in the first cluster drilled with bit size 17½ in., TCI type 5 (Pila Spi formation) were $a_5 = 0.08576$, $a_6 = -17.76926$, $(w/d)_m = 3$, $(w/d)_t = 0.0920$ and $H_1 = 1.5$. The same principle was applied to find the optimum WOB in other clusters, as shown in Appendix Table 8.

Finding optimum string rotation N

A nonlinear Eq. 31 resulted from the relationship of the RPM, Torque and Bit diameters trend lines with the depth in calculating optimal RPM as shown in Fig. 7. We assume that the trend lines described by Eqs. 24, 25 and 26 with respect to depth D for RPM, Torque and Bit diameters represent their optimum values.

$$\text{RPM}_{\text{opt}} = 574.53D_0^{-0.351} \quad (24)$$

Table 3 Maximum recommended WOB by Estes (Eren and Ozbayoglu 2010)

Maximum design weight on bit 1000 lb/in. (after Estes)													
Bit size inch	Bit class MT								Bit class TCI				
	1-1	1-2	1-3	1-4	2-1 to 2-2	2-3	3	4	5	6	7	8	9
6 1/8		5.6	6	6.6	6.9		7.9						
6¾		5.7	6.1	6.6	7.1	7.2	8.5		3.1	4.4	4.5	5.2	4
7 7/8	6	6.2	6.6	7	7.5	7.6	8.7	9.4	3.5	4.5	5	5.7	4.5
8 3/4	6.2	6.5	6.8	7.2	7.8	8	9.5	10	3.7	5.1	5.2	5.8	4.7
9 7/8	6.5	6.7	7.1	7	7.6	7.7	8.9		3.6	5.1	5.1	5.9	4.6
10 5/8		6.4		7			8.8		3.5	5	5	5.8	4.5
12¼	5.9	6.1	6.4	6.7	7.3	7.4	8.5		3.5	4.9	4.9	5.6	4.4
14¾–15		5.3		5.8		6.3	7.4		3.4	4.7	4.8	5.4	4.3
17½		5		5.7			7		3	4.2	4.2	4.8	3.8

$$\text{Tq}_{\text{opt}} = -0.0009D_1 + 10.119 \quad (25)$$

$$\text{Bd}_{\text{opt}} = 225.56D_2^{-0.406} \quad (26)$$

The coefficients in Eqs. 24, 25 and 26 are based on the actual collected data and we seek to find the optimum RPM as a function of Torque and Bit diameter. The depth values in Eqs. 25 and 26 are given by

$$D_1 = \frac{10.119 - \text{Tq}_{\text{opt}}}{0.0009} \quad (27)$$

$$D_2 = \left(\frac{\text{Bd}_{\text{opt}}}{225.56} \right)^{-2.46} \quad (28)$$

Connecting Eqs. 24, 27 and 28 by using the depth conversion $D_0 = (D_1 + D_2)/2$ gives

$$\text{RPM}_{\text{opt}} = 574.53D_0^{-0.351} \quad (29)$$

and

$$\text{RPM}_{\text{opt}} = 574.53 [5621.6 + 555.55\text{Tq} + (0.0022167\text{Bd})^{-2.46}]^{-0.351} \quad (30)$$

The averaged depth D_0 represents a choice of adding the same weight to the selectable bit diameter and the Torque parameter which mainly is controlled by the drilled formation. Equation 31 can be approximated further by fitting a trend line by trial and error to get a relation between optimum RPM with torque Tq and bit diameter Bd :

$$\text{RPM} = \text{Tq} + \text{Bd}^{1.4} \quad (31)$$

The new equation is easy to implement and contains only two variables, torque and bit diameter to the power of 1.4. Equation 31 matched all the drilled sections in 23 drilled wells in the 3 different oil blocks.

Table 4 Constant coefficient effectiveness BYM (→ balanced, ↗ significant and ↘ negative; insignificant)

Lithology no.	FM	Clusters	a_1 drillability	a_2 normal compactions	a_3 abnormal compactions	a_4 pressure differential	a_5 WOB	a_6 RPM	a_7 teeth wear	a_8 hydraulic
1	Pila Spi	9.2–137.5	↑	↑	↑	↗	↗	↑	↑	↗
2	Gercus	137.5–246								
3	Khurmala	246–330								
4	Sinjar	330–440					↑			
5	Kolosh	440–456								
6	Aaliji	456–710				↑				
7	Upper Shiranish	710–1050								
		1050–1673								
		1673–1839				↗				
		1839–1943								
8	Lower Shiranish	1943–2279								
9	Kometan	2279–2376								
10	Qamchuqa/Sarmord	2376–3635	↗	↗		↗	↑	↑	↗	↑
11	Qamchuqa/Sarmord	3635–3795	↗	↗	↗					

Results and discussion

The ROP optimization leads to the cost reduction, together with elimination of hole problems. It has been reported that drilling optimization should be based on the accumulated and statistically processed empirical data rather than working with implicit relations. All drilling parameters effecting ROP are not fully comprehended and there are difficulties to gather them in one model. For that reason, accurate mathematical model for ROP process has not so far been achieved. Many optimizations models have been considered and lead to reductions in drilling cost and decreasing operations problems. The BYM is one of the most and widely used model that has been implemented successfully among those models. BYM is one of the most important drilling optimization models because it is based on statistical synthesis of the past drilling parameters. This model is considered to be the most suitable method in drilling optimization, and it is considered as one of the complete drilling models in use of the industry for roller-cone type of bits. Through the BYM and the collected data, the optimum WOB, N and ROP were estimated.

Computer network kept the data flow directly from the different data source to the MLU on site. The multiple regression technique is used to linearly model the relationship between the dependent ROP and the eight independent parameters. Through the analysis of the drilling parameters in each cluster, a relation between the drilling parameters and ROP trend or depth were determined separately also. Many researchers worked on BYM in the past decades. Based on the scope and directions of the researches on BYM, it is possible to divide the researchers into three groups:

First group applied BYM as it is together with data limitation in different locations looking to make it suitable for specific area neglecting difference in conditions comparing to the original model condition. As a result, it has less contribution to model development (Al-Betairi et al. 1988; Bataee et al. 2010; Irawan and Anwar 2014; Kutas et al. 2015; Seifabad and Ehteshami 2013). The second group used to apply the BYM with different mathematical methods to eliminate and overcome data limitation constrain (Bahari and Baradaran Seyed 2007; Bahari et al. 2011; Nejati and Vosoughi). Some methods proved its success and others show its limitations. (Genetic a logarithm method is best of alternative method as it gives realistic and within arrange coefficients.) This paper will be under the work of third group. The third group has the best contributions to develop the BYM through considering additional drilling parameters. Modifying and reducing some drilling parameters together with high accuracy made the BYM applicable in a wider range (Bourgoyne et al. 1986; Eren and Ozbayoglu 2011; Osgouei and Özbayoglu 2007).

Table 5 Proposed drilling sections in more harmonic situations

Formations	Lithology Interval (m)	Sections drilled in Bn-1	Cluster no.	Proposed drilling sections
Pila Spi	9.2–137.5	Surface	1, 2, 3 and 4	Surface
Gercus	137.5–246			
Khurmala	246–330			
Sinjar	330–440			
Kolosh	440–456		5, 6, 7, 8, 9, and 10	Intermediate
	456–710	Intermediate		
Aaliji	710–1050			
	1050–1673	Production		
Upper Shiranish	1673–1839		11, 12, 13 and 14	Production
	1839–1943	Liner		
Lower Shiranish	1943–2279			
Kometan	2279–2376		15, 16, 17, 18, 19, and 20	Liner
Qamchuqa/Sarmord	2376–3635			
Qamchuqa/Sarmord	3635–3795

Fig. 7 Relationship between variables RPM, WOB, and bit diameter with depth

Regardless of dividing the researchers, it is observed that all researches looking for alternative solution to overcome data limitation and neglecting to look for rooms of improvement for multiple regression techniques. Most of researches applications used only tri-cone bits as original proposed model and there is a lack of verifications as it is significantly depending on statistical hypothesis tests together with absence of numerical simulation applications.

In this paper, the original BYM was used in the upperpart of the well down to 470 m where the roller cone bit was used in the drilling operation without any need to weight and bit adjustment. The same model was used for the lower part after adjusting the model for the weight and bit type. The model has been successfully implemented on each of 20 clusters. Working on a small cluster was helpful in overcoming the effect heterogeneity and the averaging process to eliminate the effect of noisy data. Some of the coefficients

Fig. 8 Modeled and original ROP for Bn-1

showed negative values in some specific intervals. Those negative values are clear indications that the effect of those parameters was insignificant.

Then, the original model was implemented directly to find the optimal WOB, while the adjusted model was used for clusters below 470 m. The new model (Eq. 31) was used to find the optimal RPM for the entire drilled well. This new model was implemented successfully on 23 drilled wells in the three oil blocks (Bazian, Taq Taq and Miran). The recorded and the predicted optimal values of ROP are shown in Fig. 8 and clearly indicate that the ROP has been optimized.

Optimized values that resulted from the work will help in performing drilling operation in the future. "Appendix 1" lists all the optimum predicted values of WOB, RPM, and ROP. The effects of all eight coefficients a_1 to a_8 are shown in Fig. 9 for the total drilled depth in Bn-1.

The effects of coefficients a_1 to a_8 have been summarized in Table 4 in order to provide a qualitative description and relation to lithologies. For example, from Fig. 9 and Table 4, it is observed that the drillability a_1 in cluster 10 was low compared to cluster 11 to indicate the hardness of Qamchuqa formation. The effect of compaction was high in cluster 10 compared to cluster 11 due to the different pressure regime between these two clusters. The effect of pressure differences was high in clusters 7 and 8 and this was due to the use of high-density fluid that was used to control the swelling and other hole problems caused by shale in clusters 7 and 8. Upper clusters 1, 2, 3, 4 and lower clusters 10 and 11 drilled were with underbalanced drilling fluid due to presence of fractures and cavities. In general, there was a good control on parameters RPM, teeth wear and hydraulic effects (a_6 , a_7 , and a_8) as they were positive range in most cases.

The efficiency of the clustering method is more visible through the drawing of the relationship between the depth and log (ROP) as shown in Fig. 8. The optimized ROP values are more stable compared with the original ROP in black color. After the completion of Bn-1, and based on the lithology similarity, we can observe that:

1. There is a high similarity between clusters 1, 2, 3, 4 and it will be more productive if they are drilled as a surface section as shown in Table 5. It will be easier if the clusters 5 to 10 are drilled as the intermediate section due to lithology similarity.
2. Production section can extend down to the top of the Kometan formation.

Conclusions

The new model to calculate the RPM is much easier than the complex models used in previous studies.

Optimization is a continuous process and the operation will be improved with the increase in the number of drilled in the specific area.

The BYM can be implemented successfully for PDC bits like roller cone bits after adjustments. A new procedure successfully introduced to find the threshold weight through instead of drill of test.

Noisy data and homogeneity assumptions eliminated through the averaging and clustering. Controllable parameters WOB, RPM, and ROP have been optimized for future operations.

Fig. 9 Range values of coefficient constant a_1 to a_8

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Glossary

Symbol	Unit	Description
a_1	Dimension less	Formation strength parameter coefficient
a_2	Dimension less	Normal compaction coefficient
a_3	Dimension less	Under-compaction coefficient
a_4	Dimension less	Pressure differential coefficient
a_5	Dimension less	Bit weight coefficient
a_6	Dimension less	Rotary speed coefficient
a_7	Dimension less	Tooth wear coefficient
a_8	Dimension less	Hydraulic coefficient
C_b	USD	Bit cost
C_r	USD	Daily rig rate
D	[L], ft (m)	Depth of borehole
d_b	[L], in (mm)	Diameter of the bit
d_n	[L], in (mm)	Bit nozzle diameter
f_1	ft/h	Rate of penetration considering formation strength function
f_2	ft/h	Rate of penetration considering formation normal compaction function
f_3	ft/h	Rate of penetration considering formation compaction function
f_4	ft/h	Rate of penetration considering pressure differential of hole bottom function

Symbol	Unit	Description
f_5	ft/h	Rate of penetration considering bit diameter and weight function
f_6	ft/h	Rate of penetration considering rotary speed function
f_7	ft/h	Rate of penetration considering tooth wear function
f_8	ft/h	Rate of penetration considering hydraulic function
g_p	[M/L ³], ppg (sg)	Pore pressure gradient of the formation
h	Dimension less	Bit tooth dullness, fractional tooth height worn away
H_1, H_2	Dimension less	Constants for tooth geometry of bit types
N	[T-1], rpm (–)	Rotary speed
Q, q	[L ³ /T], gpm (l/m)	Volumetric flow rate
ROP	[L/T], ft/h (m/h)	Rate of penetration
t_b	[T], h	Bit drilling time
t_c	[T], h	Drill pipe connection time
t_t	[T], h	Round trip time
WOB	[ML/T ²], 1000 lbf (N)	Weight on bit
w/d	[M/T ²], 1000 lbf/in. (N/m)	Weight on bit per inch of bit diameter
$(w/d)_{\max}$	[M/T ²], 1000 lbf/in. (N/m)	Bit weight per diameter where teeth fails instantaneously
$(w/d)_t$	[M/T ²], 1000 lbf/in. (N/m)	Threshold bit weight at which the bit starts to drill
ρ	[M/T ³], ppg (kg/m ³)	Drilling fluid's density
ECD	[M/L ³], ppg (sg)	Equivalent circulating mud density at the hole bottom
μ	[M/LT], cp (Pa s)	Apparent viscosity at 10,000 s ⁻¹
BYM	Dimension less	Bourgoyne and Young
IADC	Dimension less	International association of drilling contractors
MD	[L], ft (m)	Measured depth
MW	[M/L ³], ppg (sg)	Mud weight (density)
RPM	[T ⁻¹], rpm (–)	Revolution per minute
SPP	[M/(LT ²)], psi (Pa)	Standpipe pressure
TD	[L], ft (m)	Total depth
TVD	[L], ft (m)	True vertical depth

Appendix 1

See Table 6.

Table 6 Multiple regression analysis result for coefficient values

Cluster	Interval (ft)		a_1	a_2	a_3	a_4	a_5	a_6	a_7	a_8
	From	To								
1	33	351	−300	0.029	−0.049	−7.1284	0.086	−17.769	31.0	−0.36
	354	449	579	−0.057	−1.324	0.7360	0.646	0.597	6999.4	0.11
2	453	807	6	−0.004	−0.225	−11.7905	−0.627	−11.979	911.8	−1.94
3	810	1082	−1693	0.141	0.370	−1.7209	−0.046	2.479	−2890.5	−0.51
4	1086	1443	518	−0.040	0.123	−1.1540	−0.147	0.732	−2.0	−0.55
5	1446	1496	−334	0.020	−0.191	1.1957	0.003	−2.031	88.6	0.52
6	1499	1578	−92,852	8.533	4.034	0.0091	−0.030	−1.355	−18,771.3	0.01
7	1575	2326	−1	0.000	−0.003	−0.0170	0.059	0.581	−4.4	1.23
8	2326	3444	15	−0.001	0.006	0.0058	−0.085	−0.479	−3.8	0.30
9	3445	3930	−27	0.001	−0.015	−0.0256	0.153	1.742	14.0	−0.89
10	3930	5489	9	0.000	0.000	−0.0009	−0.031	3.052	3.2	−0.08
11	5490	6032	−1899	0.127	−1.778	0.0006	0.037	1.158	2.4	0.10
12	6033	6375	952	0.451	6.480	0.0033	0.047	0.059	−4917.9	3.83
13	6376	6583	−9934	2.159	6.963	−0.0009	0.013	−0.482	−14,387.5	−1.49
	6586	6670	237,856	−15.363	227.184	−0.0017	0.018	−0.402	−61.8	−1.38
14	6671	7477	−16	0.003	0.001	0.0002	−0.072	−0.234	−32.8	1.62
15	7478	7567	63,794	2.762	58.149	0.0002	−0.021	−14.578	−117,186.1	−0.79
	7570	7795	5	0.000	−0.003	−0.0001	0.130	0.334	27.3	−1.28
16	7796	8179	47	−0.005	0.006	−0.0004	0.000	0.401	82.5	−1.37
17	8180	8551	28	−0.007	0.001	0.0002	−0.056	−0.171	112.9	0.78
	8554	9863	8	0.000	−0.001	−0.0002	0.002	0.571	23.5	−1.38
18	9866	10,060	−2,311,108	521.321	−34.351	0.0001	−0.252	2.944	−8,475,415.9	0.63
	10,063	10,191	3827	0.705	4.019	0.0001	0.362	0.580	−20,471.5	1.64
	10,194	10,253	−1,214,370	520.020	602.984	−0.0002	0.579	−0.211	−9,857,148.5	−0.99
	10,253	10,716	−4370	−1.184	−3.540	−0.0003	0.051	2.122	18,105.0	−3.18
19	10,719	11,011	−31	0.015	0.001	0.0003	−0.377	0.224	−169.4	2.56
	11,014	11,551	10	−0.005	−0.004	0.0000	−0.055	0.804	74.3	0.25
	11,552	11,925	25	−0.017	0.000	0.0000	0.017	2.061	78.3	3.17
20	11,926	11,985	1,692,668	−6320.170	−13,529.655	0.0000	−2.203	−0.057	26,961,763.1	4.13
	11,988	12,143	−145,599	8.129	−433.769	0.0000	−0.299	−0.377	−4.7	−1.67
	12,162	28,857	−18,129	9.991	−41.522	0.0000	−0.014	3.771	−10,078.0	5.24

Appendix 2: Data processing steps

Tables 7 and 8 show examples of the two processing steps involved. The first step involves averaging in 10-meter

intervals for noise removal. The second step is the calculations of the eight parameters of the model.

Table 7 Data collection, preparation and 10 m averaging

Depth (m)	Depth (ft)	WOB (tons)	WOB (1000 lb)	WOB (AV 10 m)	RPM (RPM)	RPM (AV 10)	ROP (m/h)	ROP (ft/h)	ROP (AV 10)	Torque (KNm)	Flow (Gln/Min)	Flow (GPM)	M_{w-} in	Dh (in.)	Bit no.	Veloc- ity (ft/ min)	Pan PSi	ECD (ppg)	hf assumed 1/8=0.125	TFA sq.in	ΔP_b (psi)	HP	Ab bit area (si)	Av w/d lb/in.	(w/d) _i 1000 lb/in.	tb (h)
10	32.81	2.6	5.7	6.6	90	98	8.9	29.0	142.0	12.8	396.2	365.3	8.5	26.00	1-TCI	15.0	0.0004	8.5003	0.0003	1.325	536.996	124.128	530.660	0.253	0.092	0.258
11	36.09	3.3	7.3	6.7	78	101	82.2	269.6	139.5	8.6	338.2	364.8	8.5	26.00	1-TCI	12.8	0.0004	8.5002	0.0006	1.325	535.575	105.687	530.660	0.257	0.092	0.516
12	39.37	2.8	6.2	6.3	82	102	91.6	300.3	112.6	7.3	396.2	371.6	8.5	26.00	1-TCI	15.0	0.0005	8.5003	0.0009	1.325	555.619	128.433	530.660	0.243	0.092	0.774
13	42.65	2.0	4.4	6.3	88	104	65.3	214.0	82.7	10.6	396.2	365.8	8.5	26.00	1-TCI	15.0	0.0006	8.5003	0.0012	1.325	538.409	124.455	530.660	0.244	0.092	1.032
14	45.93	2.7	6.0	7.0	91	106	25.0	82.0	61.5	10.5	338.2	422.8	8.5	26.00	1-TCI	12.8	0.0004	8.5002	0.0015	1.325	719.380	141.958	530.660	0.268	0.092	1.290
15	49.21	2.0	4.3	7.2	110	109	10.5	34.3	53.4	14.3	328.6	478.1	8.5	26.00	1-TCI	12.5	0.0005	8.5002	0.0018	1.325	919.896	176.337	530.660	0.279	0.092	1.548
16	52.49	3.0	6.6	7.1	111	109	80.0	262.4	50.2	10.7	357.5	537.0	8.5	26.00	1-TCI	13.6	0.0006	8.5002	0.0021	1.325	1160.763	242.137	530.660	0.274	0.092	1.806
17	55.77	3.1	6.7	7.0	111	109	49.2	161.3	24.1	16.5	372.0	593.1	8.5	26.00	1-TCI	14.1	0.0007	8.5002	0.0024	1.325	1415.736	307.306	530.660	0.269	0.092	2.064
18	59.06	6.8	14.9	6.8	112	109	17.4	57.0	10.5	25.1	333.4	621.4	8.5	26.00	1-TCI	12.6	0.0006	8.5002	0.0027	1.325	1554.056	302.284	530.660	0.261	0.092	2.322
19	62.34	1.7	3.7	6.0	111	110	2.9	9.6	7.2	3.8	396.2	662.2	8.5	26.00	1-TCI	15.0	0.0008	8.5003	0.0030	1.325	1764.577	407.887	530.660	0.230	0.092	2.580
20	65.62	3.1	6.8	6.3	112	110	1.3	4.3	7.2	6.0	391.4	693.9	8.5	26.00	1-TCI	14.8	0.0009	8.5003	0.0033	1.325	1938.071	442.524	530.660	0.243	0.092	2.838
21	68.90	1.6	3.5	5.9	91	110	0.3	1.1	7.1	7.6	405.9	723.0	8.5	26.00	1-TCI	15.4	0.0010	8.5003	0.0036	1.325	2103.740	498.153	530.660	0.226	0.092	3.096
22	72.18	3.0	6.5	6.3	101	113	0.2	0.8	8.5	9.3	338.2	745.8	8.5	26.00	1-TCI	12.8	0.0007	8.5002	0.0039	1.325	2238.331	441.659	530.660	0.244	0.092	3.354
23	75.46	4.8	10.6	5.9	113	114	0.7	2.3	9.2	6.9	966.4	757.0	8.5	26.00	1-TCI	36.7	0.0060	8.5015	0.0042	1.325	2306.549	1300.549	530.660	0.226	0.092	3.612
24	78.74	4.0	8.8	5.4	114	114	0.42	1.4	10.3	19.8	891.3	708.7	8.5	26.00	1-TCI	33.8	0.0053	8.5013	0.0045	1.325	2021.494	1051.178	530.660	0.209	0.092	3.870
25	82.02	1.4	3.1	4.7	113	115	0.56	1.8	11.4	11.0	918.1	664.2	8.5	26.00	1-TCI	34.8	0.0059	8.5014	0.0048	1.325	1775.259	950.938	530.660	0.181	0.092	4.128
26	85.30	2.4	5.3	4.6	114	115	0.55	1.8	12.4	5.0	918.1	609.9	8.5	26.00	1-TCI	34.8	0.0061	8.5014	0.0051	1.325	1497.187	801.986	530.660	0.176	0.092	4.386
27	88.58	2.2	4.8	4.3	112	115	7.47	24.5	13.3	26.0	655.0	545.0	8.5	26.00	1-TCI	24.9	0.0033	8.5007	0.0054	1.325	1195.225	456.775	530.660	0.165	0.092	4.644
28	91.86	3.1	6.7	4.0	114	116	7.47	24.5	12.0	20.6	740.9	507.4	8.5	26.00	1-TCI	28.1	0.0043	8.5009	0.0057	1.325	1036.043	447.859	530.660	0.154	0.092	4.902

Table 8 Parameter calculations

Depth (m)	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	LN ROP (ft/h)
10	1.0	12,467	-44	-0.01	-3.19	-0.02	-0.0003	-2.1460	5.0
11	1.0	12,464	-47	-0.01	-3.16	0.01	-0.0006	-2.3068	4.9
12	1.0	12,461	-50	-0.01	-3.26	0.02	-0.0009	-2.1119	4.7
13	1.0	12,457	-53	-0.01	-3.25	0.04	-0.0012	-2.1433	4.4
14	1.0	12,454	-56	-0.01	-3.10	0.06	-0.0015	-2.0117	4.1
15	1.0	12,451	-59	-0.01	-3.04	0.08	-0.0018	-1.7949	4.0
16	1.0	12,448	-62	-0.01	-3.07	0.09	-0.0021	-1.4778	3.9
17	1.0	12,444	-64	-0.01	-3.10	0.09	-0.0024	-1.2394	3.2
18	1.0	12,441	-67	-0.01	-3.14	0.09	-0.0027	-1.2559	2.3
19	1.0	12,438	-69	-0.02	-3.34	0.09	-0.0030	-0.9563	2.0
20	1.0	12,434	-72	-0.02	-3.25	0.10	-0.0033	-0.8748	2.0
21	1.0	12,431	-74	-0.02	-3.37	0.10	-0.0036	-0.7564	2.0
22	1.0	12,428	-77	-0.01	-3.25	0.12	-0.0039	-0.8767	2.1
23	1.0	12,425	-79	-0.12	-3.38	0.13	-0.0042	0.2033	2.2
24	1.0	12,421	-81	-0.10	-3.51	0.13	-0.0045	-0.0096	2.3
25	1.0	12,418	-84	-0.11	-3.78	0.14	-0.0048	-0.1098	2.4
26	1.0	12,415	-86	-0.12	-3.84	0.14	-0.0051	-0.2802	2.5
27	1.0	12,411	-88	-0.06	-3.99	0.14	-0.0054	-0.8431	2.6
28	1.0	12,408	-90	-0.08	-4.14	0.14	-0.0057	-0.8628	2.5
29	1.0	12,405	-93	-0.08	-4.28	0.14	-0.0060	-1.0309	2.4
30	1.0	12,402	-95	-0.08	-4.70	0.14	-0.0063	-1.2199	2.4
31	1.0	12,398	-97	-0.07	-4.63	0.14	-0.0066	-1.4551	2.5
32	1.0	12,395	-103	-0.03	-5.42	0.14	-0.0069	-1.9654	2.4
33	1.0	12,392	-106	-0.04	-5.34	0.14	-0.0072	-1.9686	2.4
34	1.0	12,388	-108	-0.04	-7.69	0.14	-0.0075	-2.1708	2.3
35	1.0	12,385	-110	-0.03	-7.10	0.14	-0.0078	-2.4438	2.3
36	1.0	12,382	-112	-0.01	-6.64	0.14	-0.0081	-2.8336	2.2

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