Estimation of Rate of Penetration Considering Mechanical, Hydraulic, and Formation Characteristics for Mishref Formation

Kadhim Hmood Mnati*;Dr.Hassan Abdul Hadi**

*Missan Oil Company; **Baghdad University, College of Engineering

Abstract

This paper presents a detailed formulation of a rate of penetration (ROP) model, considering many drilling parameters and conditions for obtaining maximum drilling rate as well as minimizing the drilling cost.

A regression analysis technique has been usedfor ROP modeling in Mishref formation.The data were extracted from routinely available mud and wirelinelogs. These data includes weight on bit ,rotary speed,horse per square inch,and transit time.For ROP modeling, data of five wells inHalfaya oil field in south Iraq were extracted.Statistical software called SPSS was used for improving the modeling data and to perform linear and nonlinear multiple regression analysis. This improving approach included detection the outliers of modeling parameters, grouping the modeling data, moving average and finally applying the regression analysis.

Results of modeling showed that the grouping of modeling data exhibited good convergence with actual data and the overall model of oil field could produce good fitness with the actual data in both cases of linear and nonlinear models.Also,a good estimation of drilling cost could be obtained when using this model.

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Keywords: Drilling; Rate of Penetration; Modeling

Introduction

Most of normal drilling operations are run without quantitative techniques to determine the optimal mechanical parameters (WOB,RPM)for rate of penetration and bit life[1].This is inadequate given that ROP is becoming more and more commercially significant with increasing drilling costs and the fact that ROP and bit life can be significantly affected by subjective judgments in relation to these parameters[2].Today,the data base including depth-matched foot by foot mud logging data ,such as WOB,RPM,HIS etc.,and electric wirelinelogssuch as sonic ,Gamma ray, Resistivity and caliper are practical tools for modeling ROP and bit life. Logging data closely represent the real drilling conditions and usually readily available from exploration wells. Therefore, it is always desirable to develop drilling models from such data [3].

This paper models the ROP with mechanical, hydraulic and formation strength parameters for Misherf formation. This formation has thickness of about 460 m.Its mainly limestone interbedded (94%) with thin Marl and shale (6%). It divided into six members from top to bottom which are:Mishrif A, Mishrif B1, Mishrif B2, Mishrif C1, Mishrif C2, and Mishrif C3.The maximum ROP was 71.2 m/hr, the minimum ROP was 1.8 m/hr and the average ROP was 20.4 m/hr. while drilling this formation[4].

The parameters that included in modeling are formation strength (DT), weighton bit (WOB), rotary speed (RPM) and bit hydraulics per inch square (HSI). Data of modeling were taken from five wells (HF004-M272, HF004-n004, HF051-n051, HF109-n109 and HF195-n195) in the Halfaya oil field[4].For modeling purpose the **SPSS Statistics (**a software package used for statistical analysis)was used. This software introduces quantitative criteria to screen and organize the data, which extends ROP modeling to a wider spectrum of lithologies, limestone, and sandstone.The modeling is achieved through a multiple regression analysismethod,where the (ROP) as dependent variable and relative variables (WOB, RPM, HSI and DT) as independent variable.

Steps of Modeling ROP.

1-Removing Null Data.

Sometime, there may find some null data which should be removed for the variables of interest including ROP, WOB, RPM, HSI, and DT. Before starting to model, null data, conventionally coded as -999 by logging companies should be removed.

For the data set (5% of whole data set) null measurements, including 23 null points in WOB, 2 points in RPM and 1 point in HSI, have been removed and as a result, 469data points were left for further analysis. Table (1) shows the statistical description of the data after remove null data for wellHF004-M272.

Table (1) Descriptive set data from well HF004 –M272

	N	Range	Minimum	Maximum	Mean	Std. Deviation	Variance
Depth	469	468	2870	3338	3104.00	135.533	18369.167
ROP	469	69.40	1.80	71.20	20.3923	10.95687	120.053
RPM	469	41.00	130.00	171.00	156.90	7.77442	60.442
WOB	469	11.30	.00	11.30	7.2586	1.96530	3.862
HSI	469	2.27	.00	2.27	1.1174	.18682	.035
DT	469	45.42	49.93	95.35	69.6532	9.72448	94.565
Valid N	469						

2-**Examine the Distribution of Variables with Depth.**

Figures **(1)** through (5) depict the distributions of variables that will include in the modeling against depth, which help to examine the interaction between these variables. The common feature of these distribution is the highly fluctuation of dataset, which reflects high difficulties of evaluating the relationship between rate of penetration and drilling parameters.

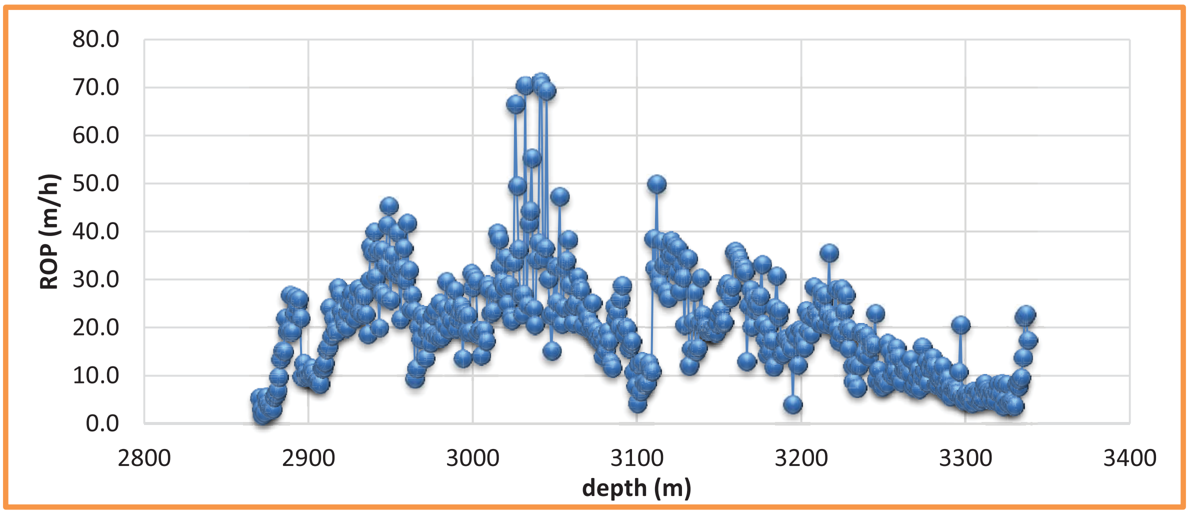


Fig.(1) Distribution of Rate of Penetration with depth.

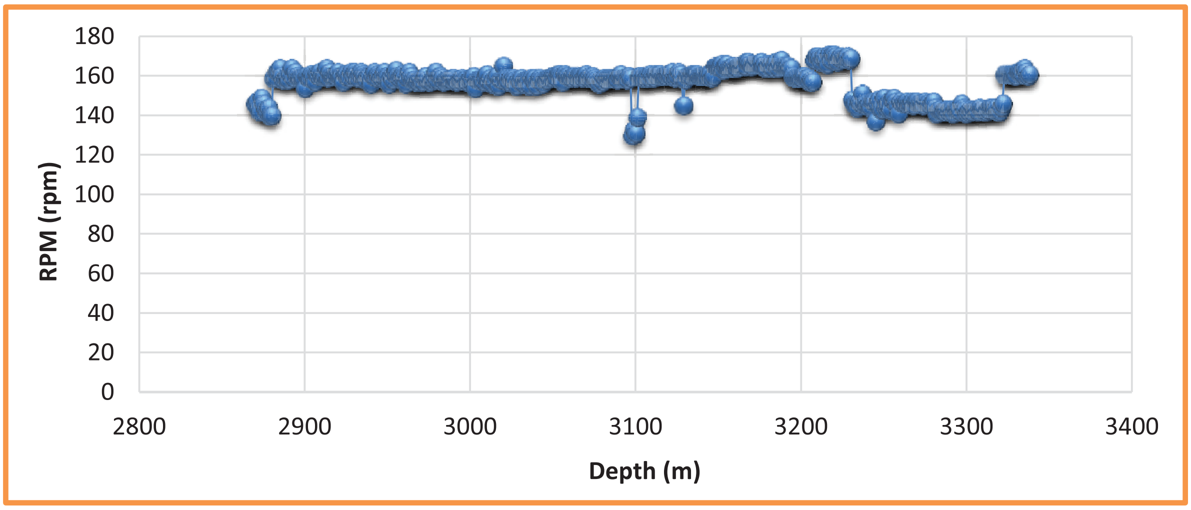


Fig. (2) Distribution of RPM with depth

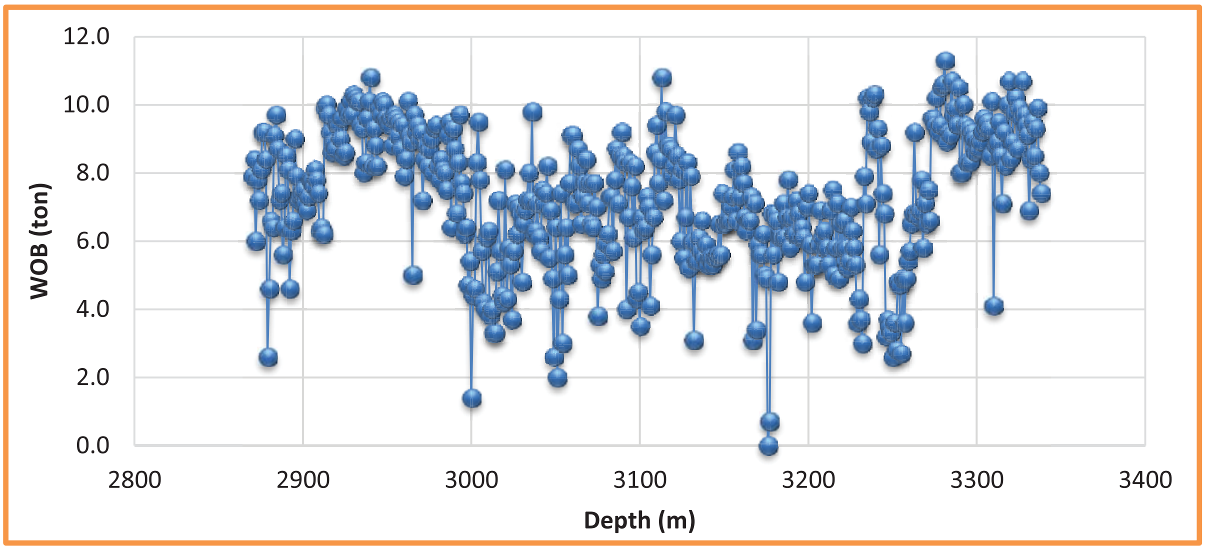


Fig. (3) Distribution of WOB with depth.

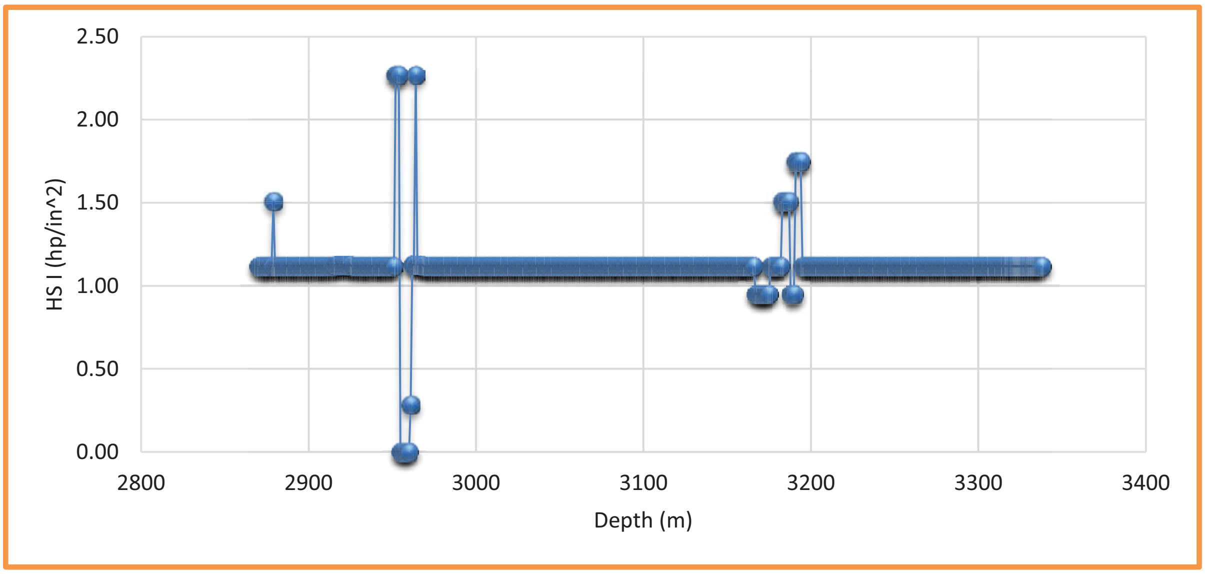


Fig. (4) Distribution of HSI with depth.

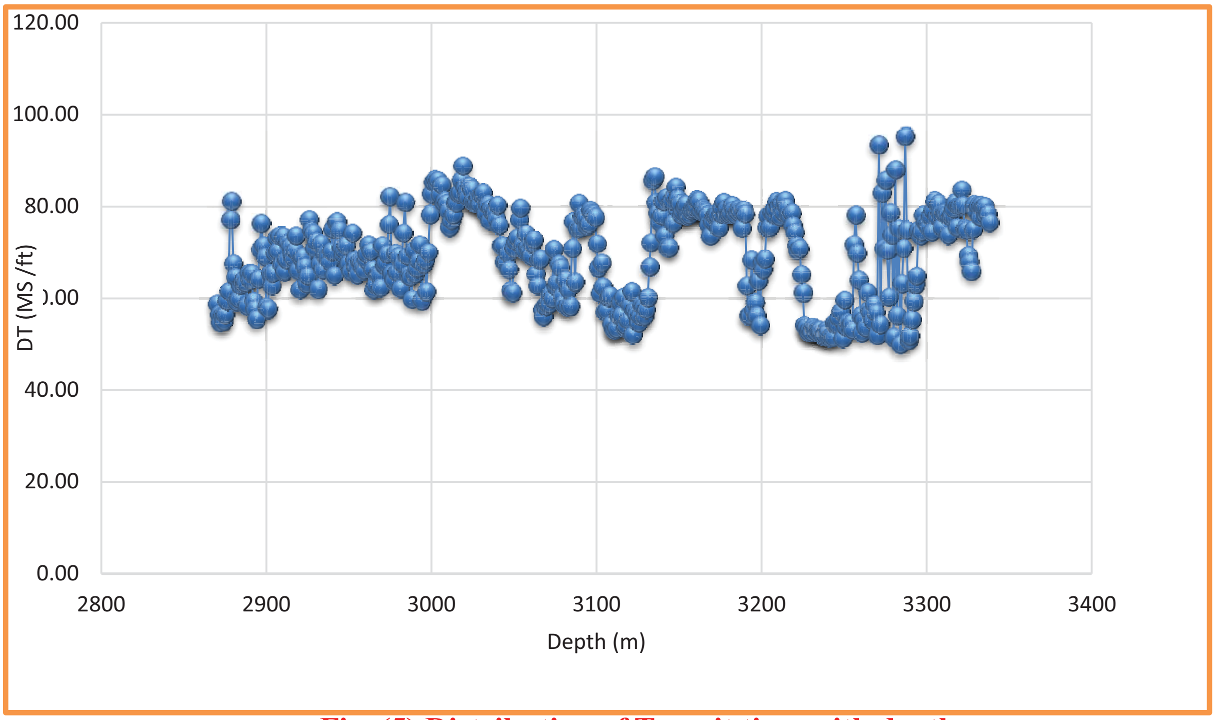


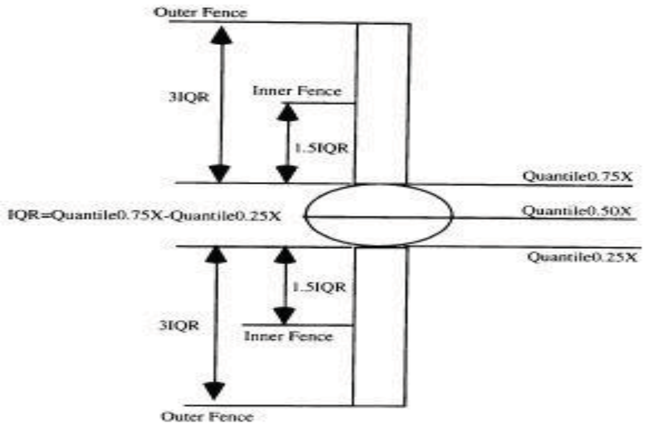
Fig. (5) Distribution of Transit time with depth.

<u>3 -Discovery of outliers.</u>

One of the most important ways that most widely used and very accurate is box plot method.Box Plot is a non-parametric method for detecting outliers. In the Box Plot, InterQuartile Range (abbreviated to IQR) is the distance between the upper (Quantile 0.75) and lower (Quantile 0.25). The IQR is calculated as:

IQR=Quantile 0.75-Quantile 0.25-------------------- (1)

Figure (6) illustrates the parameters of the Box Plot method. According to the Box Plot method, data outside the outer fences are defined as highly suspect outliers; data between the inner and outer fences as suspect outliers; and data within the inner fence are assumed to be valid data.



IQR	$IQR = Quantile_{0.75}X - Quantile_{0.25}X$	Defined as
-3	$x \le Quantile_{0.25}X - 3 \cdot IQR$	Highly Suspect Outliers
-2	$Quantile_{0.25}X - 3 \cdot IQR < x \le Quantile_{0.25}X - 1.5 \cdot IQR$	Suspect Outliers
-1	$Quantile_{0.25}X - 1.5 \cdot IQR < x \le Quantile_{0.25}X$	Normal
0	$Quantile_{0.25}X < x \le Quantile_{0.75}X$	Normal
1	$Quantile_{0.75}X < x \le Quantile_{0.75}X + 1.5 \cdot IQR$	Normal
2	$Quantile_{0.75}X + 1.5 \cdot IQR < x \le Quantile_{0.75}X + 3 \cdot IQR$	Suspect Outliers
3	$x > Quantile_{0.75}X + 3 \cdot IQR$	Highly suspect Outliers

X= Whole Data Set
x= Individual Data Point

Fig. (6) Box plot method.

Figure (7) show outliers by box plot method for each variable. According to this method, it was discovered 8 outliers for ROP variable, 25 outliers for RPM variable,3 outliers for WOB variable, 20 outliers for HSI and 0 outliers for DT variable as it is shown in the figure below.

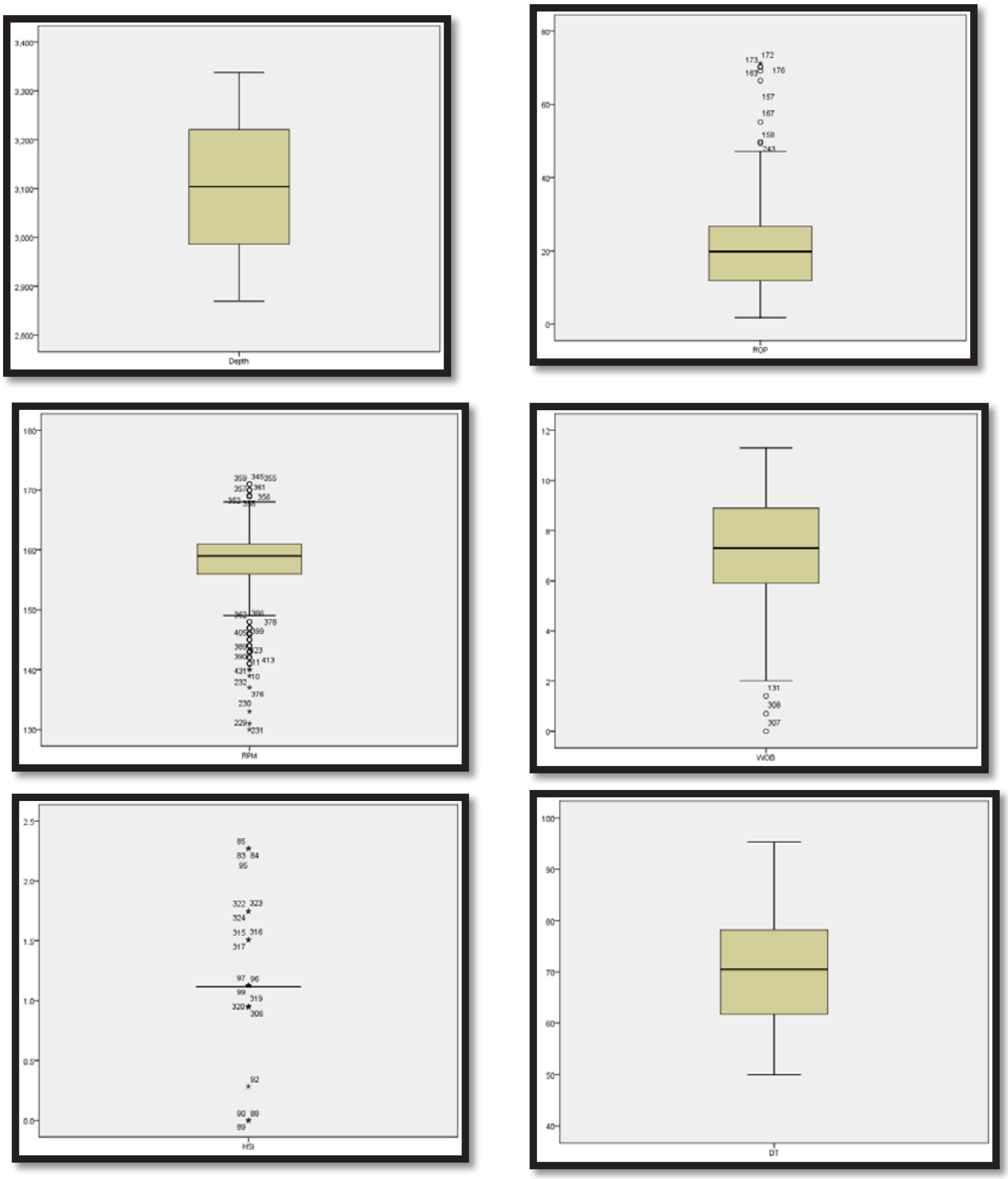


Fig. (7) Outliers of each variable in box plot method.

4- Moving – average method.

Using the moving average technique, which makes use of summation equations that are readily adaptable to computer programming, is one of the most useful techniques for smoothing data while maintaining the basic characteristics of the data for mud logging and wire line logging data. The equation of the moving-average technique is shown below:

$$x_j = \frac{\sum_{i=j}^{j+a} x_i}{1 + a} \qquad (2)$$

5-Construct Groups.

The logging data for ROP modeling can be grouped into groups of different sizes. The purpose of this step is to minimize the value of pooled-standard-error (P_{sr}) [5]. Table (2) and Figure (8) through (12) shows the values of P_{sr} for each parameter involved in the modeling. It can be seen that by increasing the group size, the effect of a few outliers on the grouped data and the value of pooled-standard-error can be decreased.

Table (2) Effect of Group Size onValues of P_{sr}.

Group size	Psr of ROP (%)	Psr of RPM(%)	Psr of WOB(%)	Psr of HS I(%)	Psr of DT(%)
1	39.02	4.32	19.74	2.46	11.02
2	20.51	0.85	12.83	0.40	5.78
3	17.25	0.82	10.53	0.39	4.77
4	16.81	0.81	5.12	0.38	1.81
6	15.90	0.81	4.98	0.36	1.77
8	12.03	0.79	4.12	0.35	1.48
12	9.28	0.75	1.23	0.34	1.17
19	8.28	0.69	0.48	0.31	0.42
24	8.38	0.66	0.47	0.28	0.40
38	7.02	0.48	0.40	0.17	0.32
57	4.63	0.26	0.31	0.00	0.25
76	3.30	0.18	0.26	0.00	0.18
114	1.81	0.11	0.22	0.00	0.08
152	1.19	0.07	0.11	0.00	0.04
228	0.59	0.04	0.06	0.00	0.01

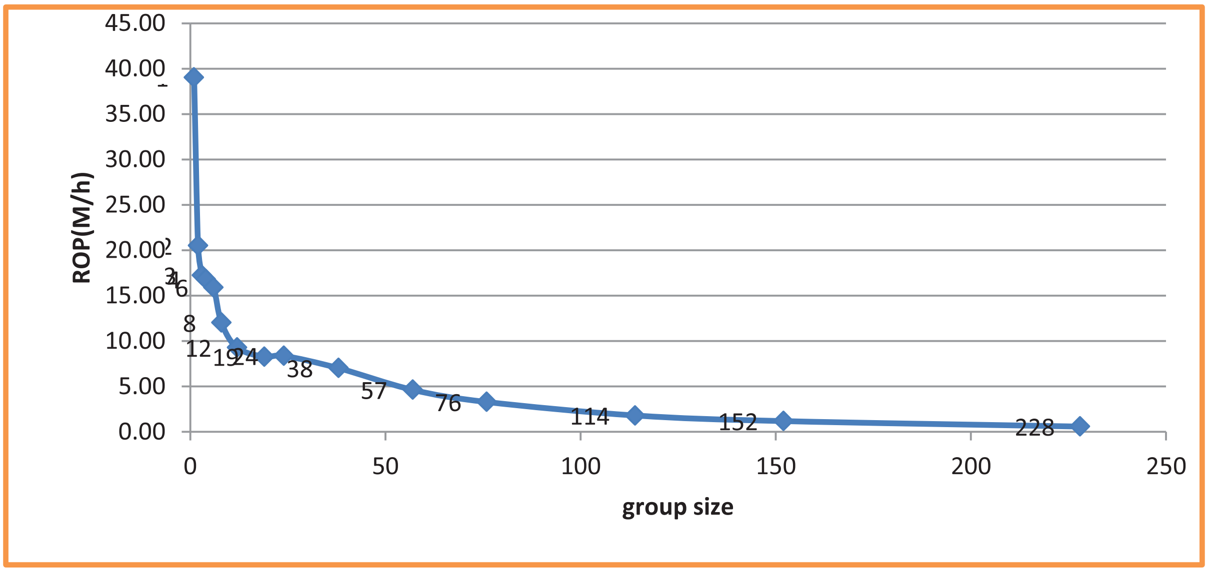


Fig.(8) shows relationship between Psr% of ROP with group size.

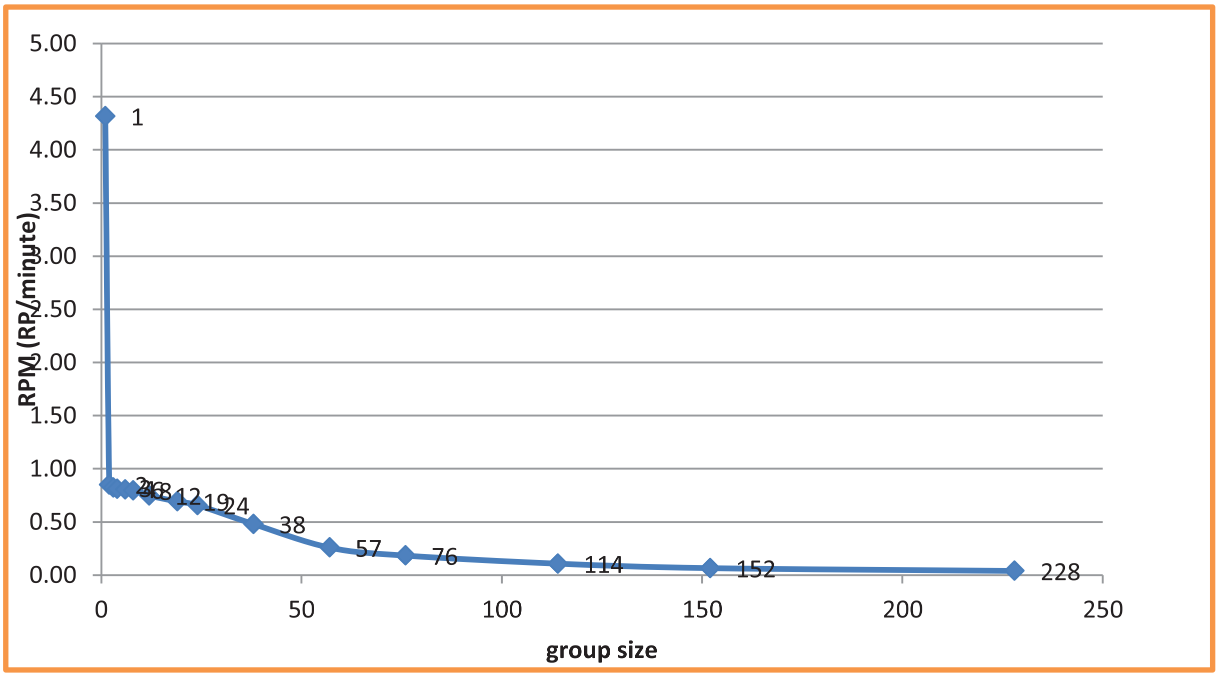


Fig.(9) shows relationship between Psr% of RPM with group size.

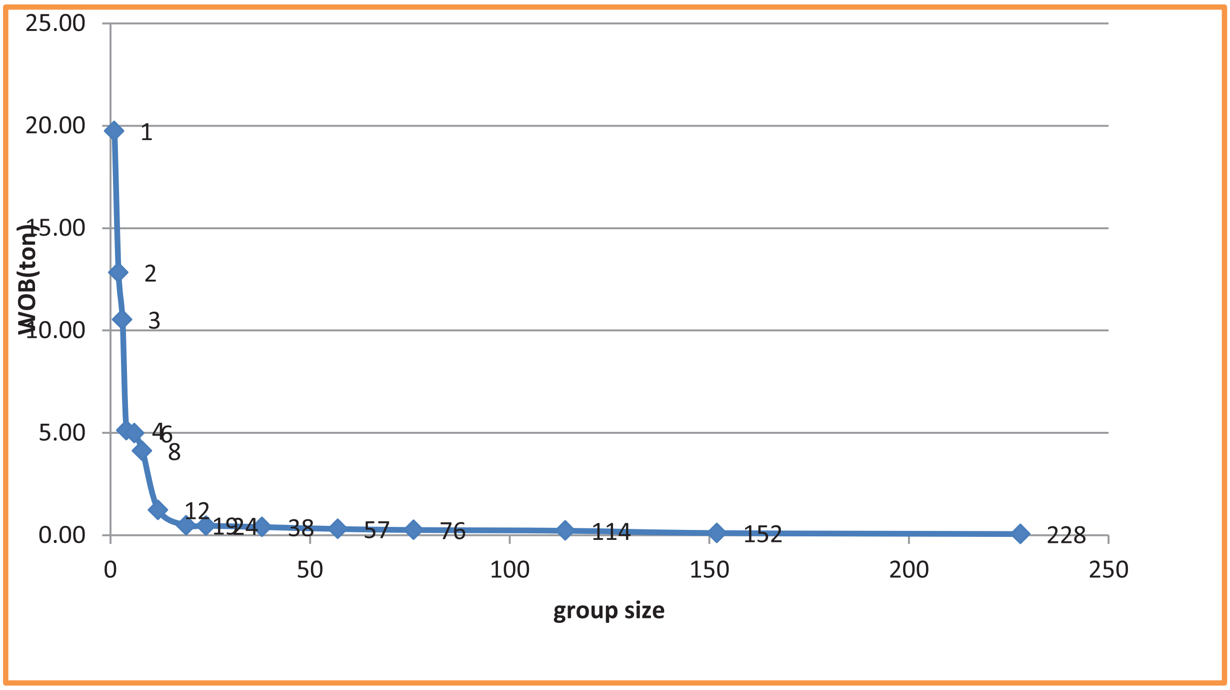


Fig.(10) shows relationship between Psr% of WOB with group size.

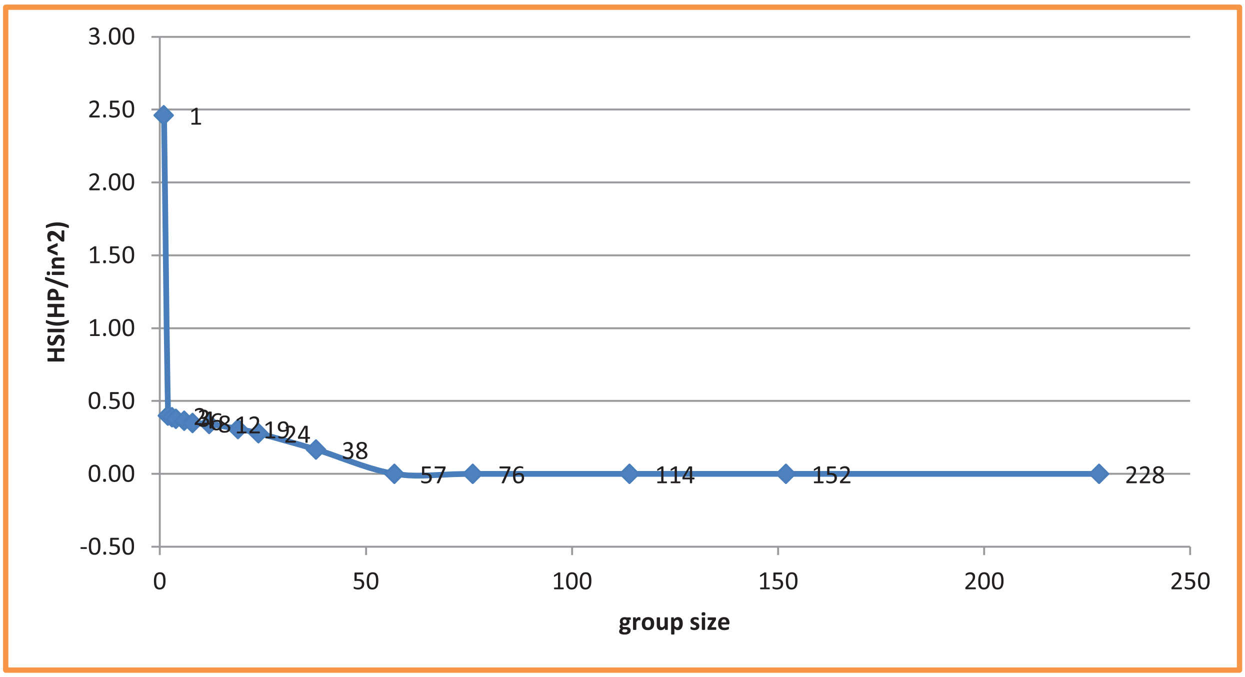


Fig.(11) shows relationship between Psr% of HIS with group size

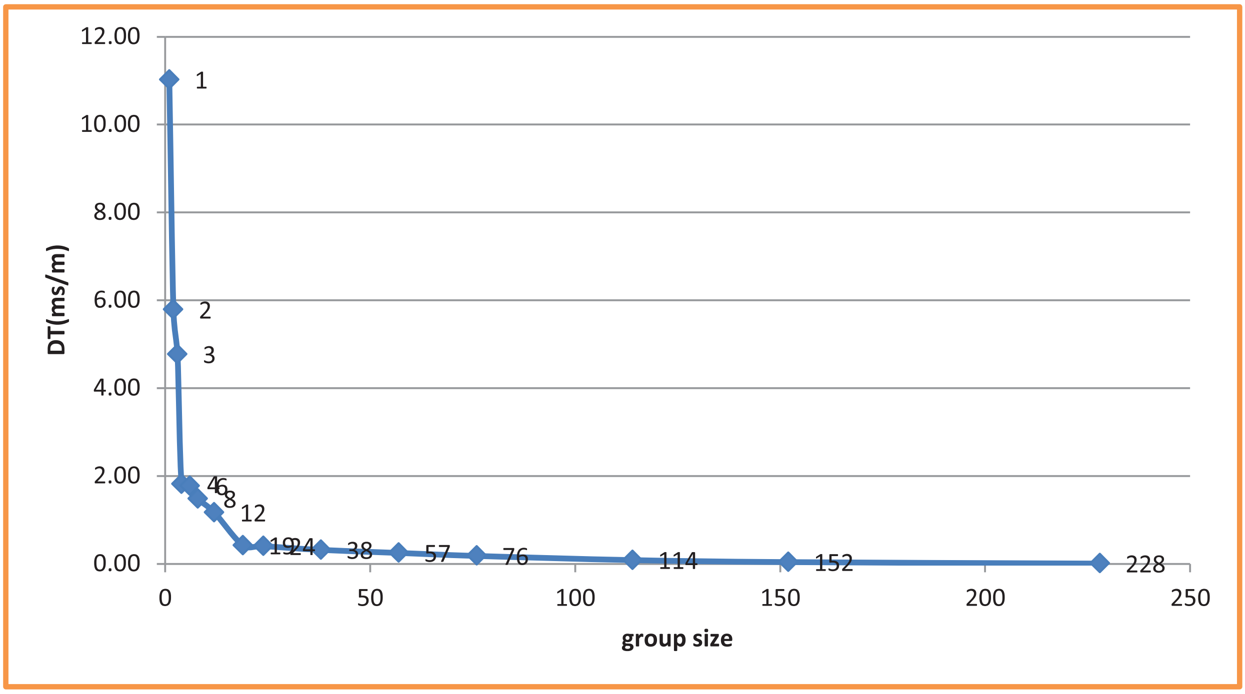


Fig.(12) shows relationship between Psr% of DT with group size

As it seen from the figures, , The largest values of P_{sr},are 39.02 % for ROP , 4.32% for RPM , 19.74 % for WOB, 2.46 %, for HSI and 11.02 % for DT.By comparison between these values of P_{sr}, it is clear that the value of ROP is largest, therefore, we can choose this variable to build the group.

In addition, when the group size reaches a certain level, increasing group-size does not efficiently reduce the value Of Psr. According to this using 19 as group size to construct group data. Table (3) show groups of each variable.

Table (3) show groups for each variables.

Depth	ROP	RPM	WOB	HS I	DT
2885	14.20	155.63	7.23	1.13	63.48
2904	13.56	159.71	7.56	1.12	67.31
2923	23.04	160.38	9.22	1.12	69.08
2942	30.94	159.90	9.43	1.12	70.29
2961	26.72	159.17	8.91	1.12	67.50
2980	21.06	158.42	8.44	1.12	68.57
2999	22.81	158.01	6.34	1.12	74.87
3018	28.91	158.30	5.35	1.12	81.98
3037	31.09	157.72	6.69	1.12	76.58
3056	28.38	159.52	6.38	1.12	69.71
3075	20.09	158.85	6.61	1.12	63.22
3095	15.98	158.21	6.73	1.12	72.06
3114	27.69	159.87	7.94	1.12	57.06
3133	24.76	159.52	6.13	1.12	69.14
3152	24.86	163.51	6.65	1.12	79.18
3171	25.25	165.60	5.94	1.06	78.25
3190	17.82	163.70	6.34	1.19	70.42
3209	22.24	164.60	5.94	1.12	75.38
3228	18.85	160.79	6.26	1.12	59.67
3247	13.23	145.44	5.66	1.12	55.43
3266	10.99	146.05	6.99	1.12	62.63
3285	9.54	143.57	9.49	1.12	67.83
3304	6.67	142.87	8.83	1.12	75.80
3323	6.68	152.79	9.16	1.12	76.81

6-Perform Multiple Linear Regression Analysis.

A linear regression analysis is performed since it is simple to apply and straightforward to interpret. The leverage plots, figures depicting the contribution of individual variables to ROP variations, and the ROP residuals can indicate the suitability of a model and may suggest how the model could be improved.Based on the foundation of drilling mechanism, variables including

WOB, RPM, HSI and DT are chosen as the independent variables while ROP as the dependent variable for regression analysis. Table (4) and figure (13) shows the results of regression analysis of modeling data. The fitness of the model to the grouped data is very good. This is evident through R^2 (0.919) and RMSE (2.46). The following equation (3) represents the model of data (Mishref formation).

$$ROP = -26.4 + 0.76RPM + 0.27WOB - 57.6HSI - 0.17DT \quad (3)$$

Table (4) Results of regression analysis for group data.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	RMSE
1	.958[a]	.919	.864	2.46311	2.46

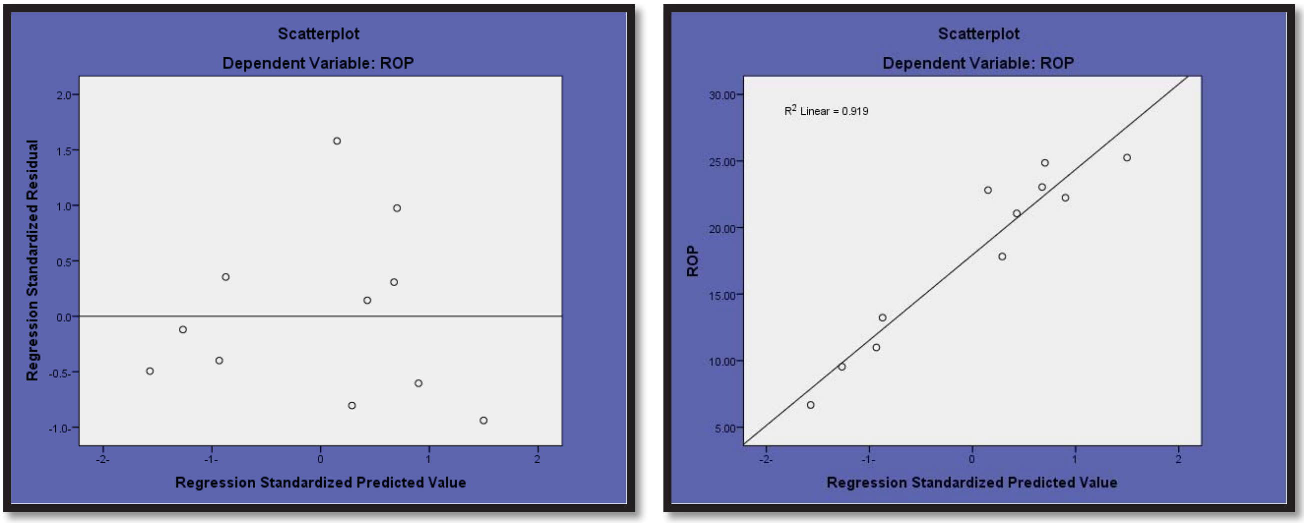


Fig. (13) Show residuals and predicted value for regression analysis.

Figure (14) and figure (15) show the comparison between actual data with fitted data in grouped and raw data. As it seen from figure (14), grouping of logging data for ROP modeling achieved a good correspondence between the two, while ungrouped data Figure (15) did not achieved this correspondence.

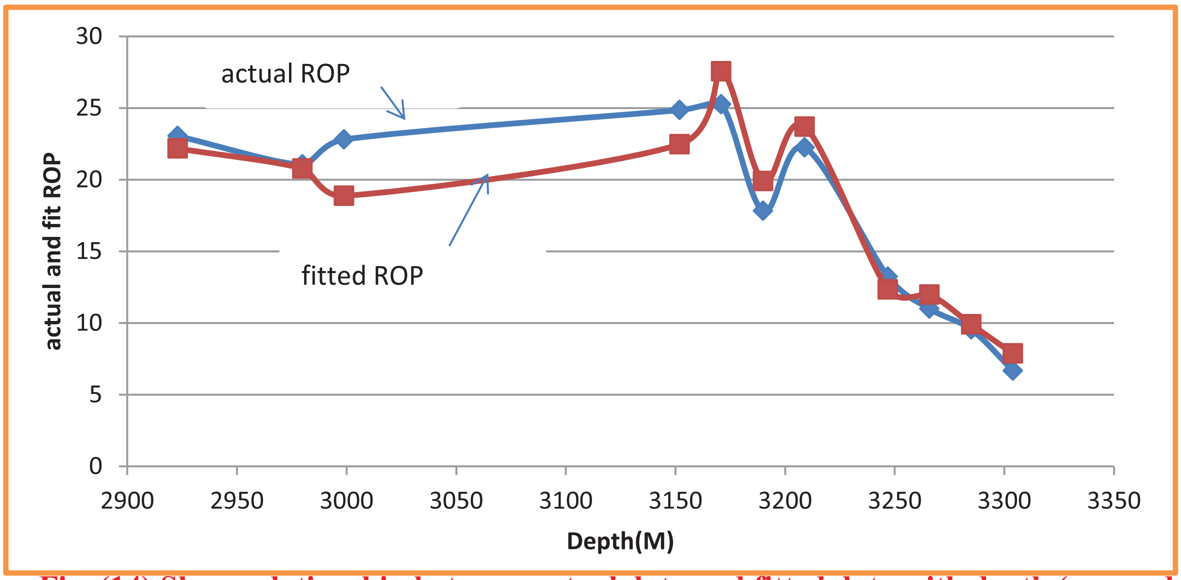


Fig. (14) Show relationship between actual data and fitted data with depth (group data).

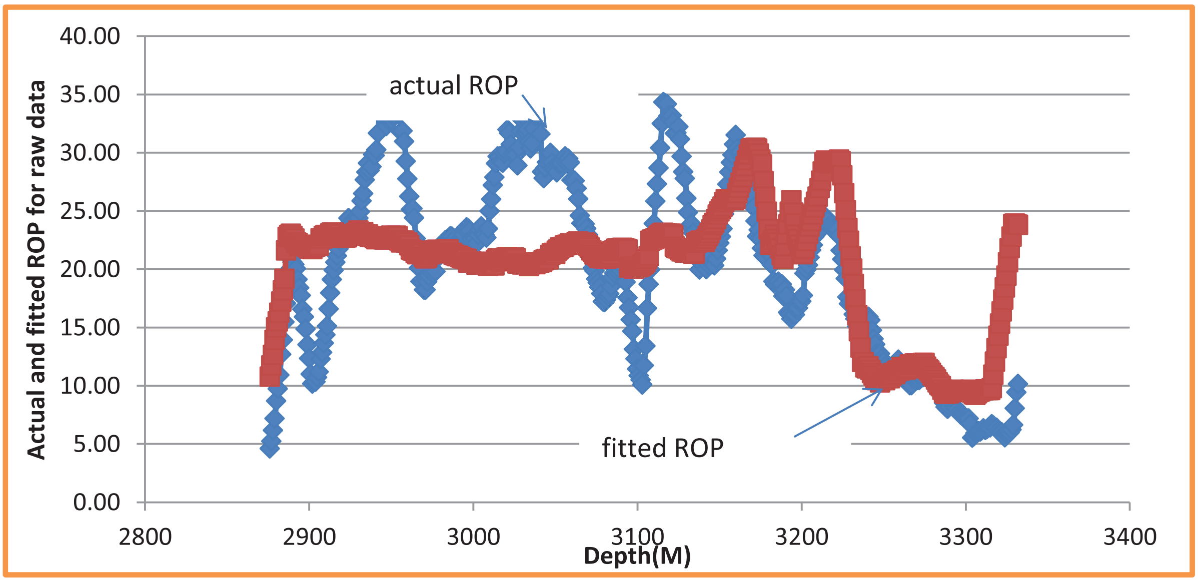


Fig. (15) Show relationship between actual data and fitted data with depth (raw data).

well HF272-M272.The data of wells HF004-N004, HF051-N051, HF109-N109 and HF195-N195 were analyzed and divided into four groups in the same way that used in the previous analysis. After obtaining the final results for each well the datasets were combined for each group to drive overall model for field. To determine the form of the combined model, the exercise below is conducted according to regression analysis for each group. These models are:-

a. Linear model:-

$$ROP = -109.31 + 3.71 \times WOB + 0.19 \times RPM + 0.1 \times HSI + DT$$

Results: - R^2=0.89 , RMSE = 2.8

b. Nonlinear model:-

$$ROP = 2.7 \times 10^{-13} \times WOB^{1.345} \times RPM^{1.957} \times HSI^{0.063} \times DT^{4.6}$$

Results: - R^2=0.9 , RMSE = 2.7

Estimation of bit run cost

This function is summarized by cost per foot, Eq(4) [6]. This equation has been commonly employed by the drilling community (Bourgoyne, et al 1986, Fear, et al 1992; Graham, et al, 1959, Moore, 1958).

$$\mathbf{C_f} = \frac{\mathbf{C_b + C_r(t_t + t_c + t_b)}}{\mathbf{\Delta h}} \quad (4)$$

And $\Delta h = ROP \times t_b$ (5)

Hence $\mathbf{C_f} = \frac{C_b+C_r(t_t+t_c+t_b)}{ROP \times t_b}$ **(6)**

For a given bit run, bit cost is a constant, footage (Δh) is a function of both rate of penetration (ROP) and bit life (t_b) and the variations of connection time (t_c) and trip time (t_t) are relatively insignificant. Hence, the cost per foot is effectively determined by ROP and t_b. Since both ROP and t_b are functions of a number of other drilling variables, such as weight on bit (WOB), rotary speed (RPM), and so on it follows that the ability to model ROP and t_b mathematically is a precursor to cost-based optimization. However, Choose the data of the well (HF004-M272) in order to be available by the following information:-

Cost of rig is 30000$/day.

Cost of BIT is 5000$.

Drilling time is 16 hour (0.66 day).

Trip time is 1.5 hour (0.0625 day).

Time connection is 1 minute (0.017 hour).

Figure (16) displays the results of drilling cost per meter by classical form and by regression analysis method (model). There is clearly a very good correspondence between the two.

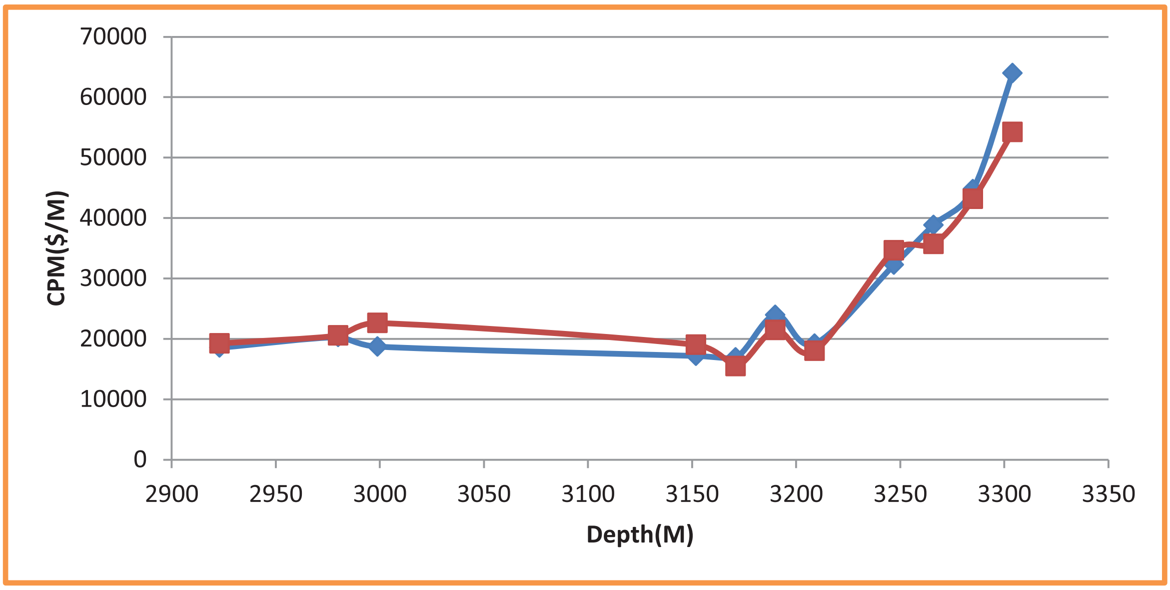


Fig. (16) Show $C_f$of actual data and fitted data with depth (group data).

Conclusions

1- A rate of penetration model for Misherf formation in HALFIA oil field was constructed considering mechanical, hydraulic, and formation strength.

2- Grouping of logging data for ROP modeling can improvedthe fitness the model when compared to ungrouped data.

3- The linear model shows good fitness when compared with the measured data.

4- The overall model for the oil field shows good fitness in cases of linear and nonlinear models when compared with the actual data.

5- A high fitness of the new model was obtained through the estimation of the cost of drilled footages.

Monenclature

C_f=Cost per Meter,$/m

C_b=Bit Cost,$

C_r=Rig Cost,$/hr

DT=Acoustic transit time,µsec/ft

HIS=Horsepower Per square Inch of Bit,hp/in^2

IQR=Inter Quartile Range

P_{sr}=Pooled Standard Error

RMSE=Residual Standard Error

ROP=Rate of Penetration,m/hr

Rpm=Bit Revolution per Minute

T_t=Trip Time,hr

T_c=Connection Time,hr

T_b=Trip Time,hr

WOB=Weight on Bit,ton

Δh=Length of drilled interval,m

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