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Studying empirical correlation between drilling specific energy and geo-mechanical parameters in an oil field in SW Iran

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Abstract

Multiplicity of the effective factors in drilling reflects the complexity of the interaction between rock mass and drilling bit, which is followed by the dependence of parameters and non-linear relationships between them. Rock mass or, in other words, the formation intended for drilling, as the drilling environment, plays a very essential role in the drilling speed, depreciation of drilling bit, machines, and overall drilling costs. Therefore, understanding the drilling environment and the characteristics of the in-situ rock mass contributes a lot to the selection of the machines. In this work, a 1D geo-mechanical model of different studied wells is built by collecting the geological data, well logs, drilling data, core data, and pressure measurements of the formation fluid pressure in various wells. Having the drilling parameters of each part of the formation, its specific energy is calculated. The specific energy index can be used for predicting the amount of energy consumed for drilling. In order to find the relationship between the drilling specific energy (DSE) and its effective parameters, the multivariate regression model is used. Modeling DSE is done using the multivariate regression, which contains the parameters rock characteristics, well logs, and a combination of these two features. 70% and 30% of the data are, respectively, selected as the training and test for validation. After analyzing the model, the correlation coefficients obtained for the training and test data were, respectively, found to be 0.79 and 0.83. The parameters uniaxial compressive strength (UCS), internal friction angle, and fluid flow are among the most important factors found to affect DSE.

Keywords: *Drilling Specific Energy, Multivariate Regression, Geo-Mechanical Properties, Well Logging.*

1. Introduction

The concept of rock specific energy (SE) was first introduced by Teale (1965), who proposed it as a measure of the mechanical performance of the rock grinding tools. Defined as the amount of energy required to grind unit volume of a rock, the specific energy concept has been widely used as a measure of the drilling machines' efficiency in terms of rock drilling performance in the rock studies and projects. Teale (1965) has suggested that one can enhance the drilling efficiency by minimizing SE. In the rotary drilling, breaking the rock into over-small fragments leads to the over-consumption of energy [1]. Rabia and Farrelly (1987) have used SE as a measure to indicate the formation property variations, and also to prepare a basis to choose the drilling bit according to the drilling performance [2]. Huang and Wang (1997) have proposed an equation for calculating the required SE to have a given rock grinded using coring bits. They have found that in lower weight-on-bit (WOB), a part of energy is lost due to friction; furthermore, an increase in WOB is associated with a respective increase in the torque, while reducing DSE. They have reported that there is an optimum WOB, at which SE is optimized [3]. Ersoy and Atici (2001) have studied the rotary rock cutting machine, and have revealed that one can use the mechanical specific energy to evaluate the productivity of a wide range of grinding applications. An increase in the rate of penetration (ROP) is associated with a decrease in the mechanical specific energy, while an increase in cutting depth leads to a reduction in the specific energy [4].

By the mid-2000s, the commercial interests caused the development of sophisticated logging techniques, and the drilling efficiency was improved through experiencing trial and error. Improvements in drilling became possible through innovations in all aspects of the industry including the bit design, drilling fluid, rig design, and many other parameters. The MSE method began to emerge for improving the efficiency of drilling at all levels including rigs and bits, and hence, industrial researchers began to study this metric. Although industrial research works began using MSE evaluation heavily, academic researchers did not give it the same level of importance, with some exceptions [5].

Caicedo and Calhoun have created a method to predict ROP of a given bit using MSE, and have successfully tested the method on rigs in 2005 using the real time data [6]. In 2005, DuPriest and Koederlitz have undertaken an extended investigation on the use of mechanical specific energy to optimize ROP. They used the drilling operation data to calculate the mechanical specific energy, by which they corrected the well log data. Since they succeeded to improve the drilling efficiency by monitoring the mechanical specific energy, they took the energy as a standard for monitoring the drilling operation data [7, 8].

Furthermore, Armenta (2008) has suggested that hydraulic is an important factor that should be accounted for in the equation for DSE. In other words, Armenta (2008) believed that bit hydraulic contributed to the increased penetration of the bit into the formation and enhanced the drilling efficiency. The rock tends to be grinded by the mechanical energy, with the cuttings removed from the bit face by the drilling fluid. The faster the cuttings are removed, the lower will be the required energy for having those re-drilled [9].

$$DSE = \frac{WOB}{A_B} + \frac{120 \times \pi \times RPM \times Torq}{A_B \times ROP} - \frac{1980000 \times HF \times HP}{ROP \times A_B} \quad (1)$$

where DSE denotes the drilling specific energy (in lb-ft/ft^3), *WOB* is the weight-on-bit (in lb), *RPM* is the rotational speed of the drill string (in rpm), *ROP* is the rate of penetration (in ft/hr), A_B refers to the involved area of the bit (in in^2), *T* denotes the torque (in lb-ft), *HF* is the hydraulic factor of the bit, and *HP* represents the hydraulic power rate of the bit (in hp).

Hamrick (2011) conducted numerous experiments to optimize the drilling parameters. By optimizing the controllable parameters, he succeeded to minimize the mechanical specific energy, leading to a maximized ROP [10]. Amadi and Iyalla (2012) have used the optimization techniques for mechanical specific energy to reduce the drilling costs. They optimized the resulting specific energy by predicting an optimized ROP from the logging-while-drilling (LWD) data as well as the inherent formation data. In areas where accurate data is available from adjacent wells, one can use the corresponding ROP to the area as a base for optimizing the cost [11]. Laosripaiboon et al. (2015) have used the down-hole specific energy and well logging data for choosing the perforated zone by avoiding the low potential zone [12]. Wei et al. (2015) have studied the specific energy for the drilling and pulse jet. Through theoretical analysis and laboratory experiments, the MSE model for pulsed-jet drilling was established. According to the MSE theory, the major influences of the pulsed-jet are changing the breaking strength of rocks and are improving the cleaning efficiency down the hole as well as showing a good power function between MSE and the rate of penetration in pulsed-jet drilling [13].

After preparing the raw data and calculating DSE from the drilling data, in the next step, the rock mechanics parameters should be calculated. Laboratory studies and direct measurements are the most reliable ways to determine the mechanical properties of rock mass. However, due to the unavailability of core drilling, especially in the oil industry, using and relying on the results of empirical dynamic relations is the only way to estimate the rock properties.

For relating DSE to the geo-mechanical parameters of the formation, mathematical models could be used. These models may be linear or non-linear. If we can write the correlation pattern in the form of a linear equation, it is called the linear regression equation. Regression analysis is one of the most common methods implemented for solving linear and non-linear problems, which has made its use in modeling various issues. The artificial intelligence techniques such as the neural networks and fuzzy neural networks can also be used to solve the complex non-linear problems. In this work, non-linear regression is used to determine the relationship among the parameters. The features of the empirical relationships can be of low cost and data integrity throughout the reservoir [14].

There are many factors that can influence DSE. In this paper, due to the lack of access to image logs, the effect of joints and cracks on DSE were not considered. The drilling rigs and drilling bits used for both wells were identical and belonged to one contractor, so the working conditions were not correspondent.

2. Utilized well data

The data for this research work was obtained from the vertical wells in one of the oil fields in SW Iran. During the conducted survey, it was found that the petro-physical logging and drilling data had a common range in a depth of 3528 to 3875 m in well No. 1 and a depth of 2700 to 3230 m in well No. 2, which belonged to the Asmari formation. Hence, studies were conducted in these special depths. The number of finalized data for assessments in wells No. 1 and 2 was, respectively, 347 and 533, which were related to the Asmari reservoir formation. In the data analysis, the values outside the standard deviation were removed and not considered in the final analysis.

Drilling operation is one of the most costly activities of the upstream oil industries, which has a special function in this industry. These costs can be reduced by increasing the drilling efficiency. Several factors influence the efficiency of drilling, DSE and rat of penetration (ROP) being considered as the most important ones. The best drilling efficiency is achieved when DSE is reduced by increasing the penetration rate. Hence, drilling will have the highest performance with the least energy consumption. Here, the impact of each parameter involved on DSE is discussed.

3. Qualitative Study of factors affecting DSE

After determining the parameters affecting DSE and selecting them as the inputs for modeling, the next step was to assess qualitatively their relationship. In Figures 1 and 2, the diagrams of DSE and its effective factors are shown. According to these figures, in wells (1) and (2), with increase in the rock strength, the Young's modulus, internal friction angle of the rock, and DSE also increased. Reduction in the fluid flow rate left the cuttings at the bottom of well, which, in turn, caused regrinding cuttings at the bottom of well and greater energy consumption. Changes in DSE and other influencing parameters with respect to the depth are shown in Figures 1 and 2. It should be noted that some parameters interact with each other.

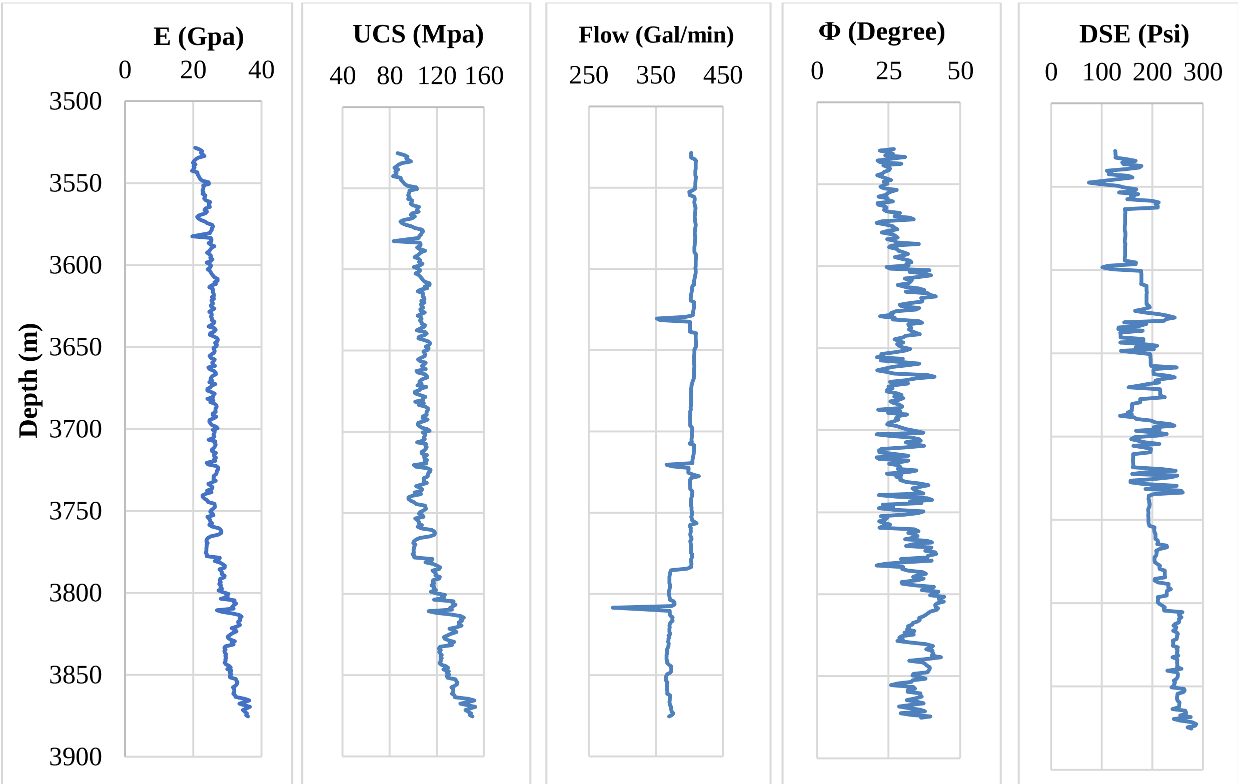

Figure 1. Drilling specific energy and influencing parameter variations with respect to depth in well No 1.

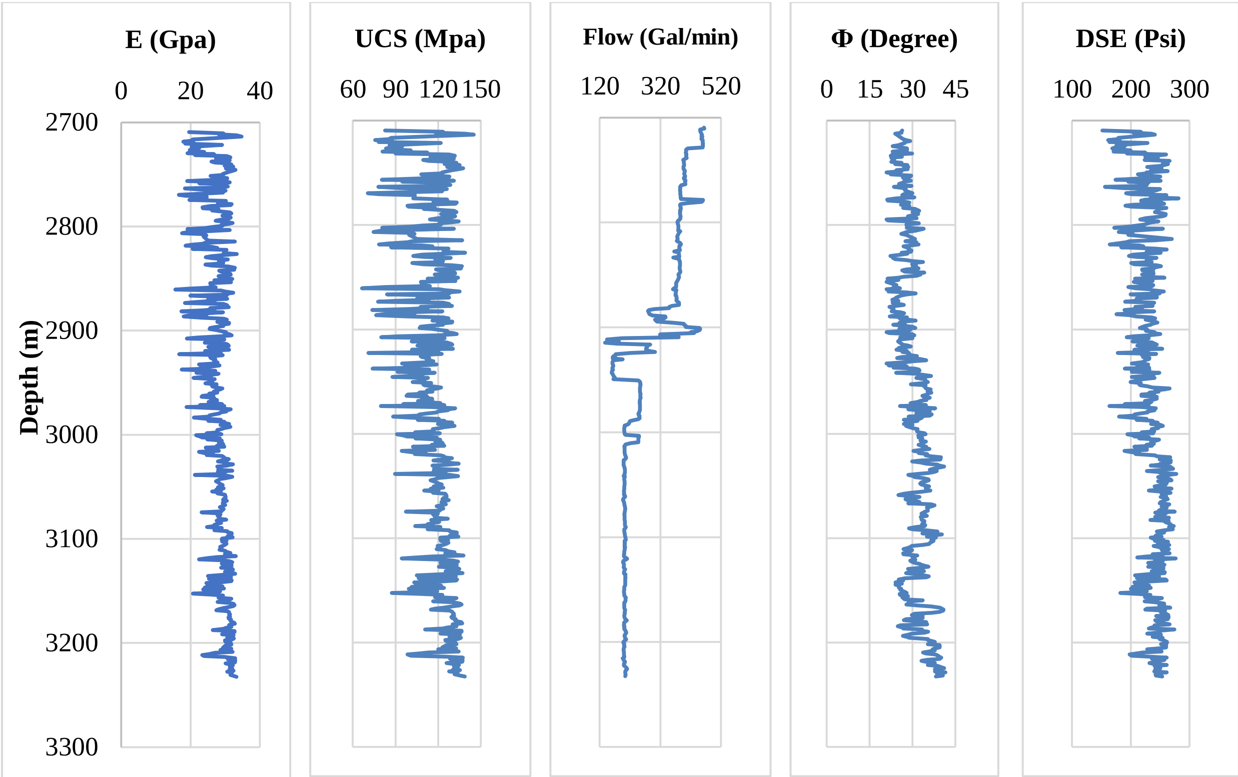

Figure 2. Drilling specific energy and influencing parameter variations with respect to depth in well No 2.

4. Quantitative analysis of effects of geo-mechanical parameters on DSE

Processing the data and converting them into the required information provides a decision-making context. The manager and expert skills have appeared in the use of statistical methods and data analysis. Nowadays, without the use of statistical methods, we are hardly able to analyze, explain, and interpret the results of the scientific research works and studies. Statistics is a branch of mathematics that includes the collection, analysis, interpretation, and display of groups of numerical data. With this science, we can predict the future behavior of a process using the past information as well as the available mathematical and probability models. This science is mainly concerned with the conditions where the occurrence of an event cannot be conclusively predicted [15]. In statistical models, regression analysis is a statistical process used to estimate the relationship between the variables. It involves many techniques for modeling and analysis of certain and unique variables. When focusing on the relationships between a dependent variable and one or more independent variables, considering that these variables can have relationships with each other, their relations can be found and evaluated using regression and modeling.

In this work, the multivariate linear and non-linear regressions were used to study the relationship between the variables and the target parameter. 70% and 30% of the total data were, respectively, considered as training and testing for model validation. First, each geo-mechanical characteristics of rocks were studied for the training and testing data. Combining the geo-mechanical variables of the rocks, a general model was presented for the dependent variable of DSE, and the test data was finally used to validate the general model.

4.1. Studying effects of geo-mechanical parameters on DSE

In this section, before presenting the model, the type of relationship between each one of the independent variables and the dependent variable is discussed. Then the best linear and non-linear combinations are presented for model prediction after removing the co-linearity between variables. The scatter plot for the dependent and independent parameters and their relevant tables including the model summary and equivalent coefficients are given in each section. Various models were fitted to the data for the dependent and independent variables, and according to the scatter plot and the values for the correlation coefficients, coefficient of determination and adjusted coefficient of determination of the model

were selected with minimum error versus other models. In Tables 1-4, equations for the relationship between each operational parameter and DSE as well as their correlation coefficients are listed.
Investigation of the training and testing data showed that the inherent cohesion, internal friction angle, depth, pore pressure, Young's modulus, and UCS had direct relationships with the drilling specific energy.
The fluid flow parameter and Poisson's ratio had inverse relationships with the drilling specific energy, as well. The pressure sonic log, shear sonic log, and porosity logs had inverse relationships with DSE for both the training and test data. The presented correlation coefficients reflect the relationship between the variables and the target parameter. The overview for representing a model of geo-mechanical variables of the formation on DSE revealed that the best available linear and non-linear combinations that could appear in the final model include the interaction of the parameters involved and their effect in the order form of one, two, and three.

4.2. Studying hybrid model of geo-mechanical parameters regarding DSE for training data

In order to provide a model of variations of rock characteristics on DSE, an overview was done, which revealed that there was a high co-linearity between some of the variables. One major reason for this co-linearity is the estimation of the most geo-mechanical parameters of pressure wave velocity, density, and porosity logs. To remove co-linearity, the effective variables were identified, and the variables of high co-linearity were removed from the model step by step. Finally, the model achieved an the overall coherence and the final result of regression analyses between the dependent variable characteristics of DSE and the independent variable of rock characteristics are provided in Table 5.
From the equations presented in Table 5, equation (24) is the best relationship for the drilling specific energy due to the high correlation coefficient. However, in the analysis of the F and T tests, with respect to non-significance of the equation, it is disregarded. Equation (23) is the most appropriate hybrid model of geo-mechanical parameters for predicting the drilling specific energy. The multiple correlation coefficient of the model was 0.79. In this model, UCS, the internal friction angle of the rock, and the fluid flow were the effective variables appearing in the equation after removing the co-linearity and predicting the dependent variable. The F and T tests have become significant as the model coefficients of equation (23). Tables of model pattern analysis, analysis of variance (ANOVA), and regression coefficients are provided in Tables 6-8.

Table 1. Relationship between geo-mechanical rock characteristics and drilling specific energy for training data.

Correlation coefficient	Parameter relationship equation with drilling specific energy	Parameter	Equation
0.63	$DSE = 81.285 \times e^{0.0356\ E}$	Young’s modulus (Gpa)	(1)
0.67	$DSE = 74.387 \times e^{0.0093\ UCS}$	UCS (Mpa)	(2)
0.65	$DSE = 0.2937 \times e^{0.0018D}$	Depth (m)	(3)
0.63	$DSE = 306.17 \times e^{0.001\ FLOW}$	Flow rate (Gal/min)	(4)
0.67	$DSE = 1481.9 \times \ln(PoreP) – 12200$	Pore pressure (psi)	(5)
0.35	$DSE = 138 \times e^{0.013\ C}$	Inherent cohesion (Mpa)	(6)
0.30	$DSE = 154\times e^{0.0102\ PHI}$	Internal friction angle (Degree)	(7)
0.14	$DSE = 168.4\times(Poisson)^{0.132}$	Poisson	(8)

Table 2. Relationship between petro-physical log data and drilling specific energy for training data.

Correlation coefficient	Parameter relationship equation with drilling specific energy	Parameter	Equation
0.68	$DSE = 5470.7 \times e^{-0.063\ DT}$	Pressure sonic log (Us/ft)	(9)
0.55	$DSE = 100.5 \times e^{-0.0003\ DTs}$	Shear sonic log (Us/ft)	(10)
0.10	$DSE = 0.1193 \times (NPHI)^{-0.034}$	Porosity log (dec)	(11)

Table 3. Relationship between geo-mechanical rock characteristics and drilling specific energy for test data.

Correlation coefficient	Parameter relationship equation with drilling specific energy	Parameter	Equation
0.82	$DSE = 113.73 \times e^{0.0247\ E}$	Young's modulus (Gpa)	(12)
0.84	$DSE = 109.7 \times e^{0.0062\ UCS}$	UCS (Mpa)	(13)
0.41	$DSE = 0.1963 \times e^{0.8849\ D}$	Depth (m)	(14)
0.35	$DSE = 263.25 \times e^{-0.0003\ FLOW}$	Flow rate (Gal/min)	(15)
0.15	$DSE = 113.9 \times \ln(PoreP) - 717.9$	Pore pressure (psi)	(16)
0.57	$DSE = 57.99 \times C^{0.395}$	Inherent cohesion (Mpa)	(17)
0.32	$DSE = 194.36 \times e^{0.0063\ PHI}$	Internal friction angle (Degree)	(18)
0.14	$DSE=172.8 \times (Poisson)^{-0.163}$	Poisson	(19)

Table 4. Relationship between petro-physical log data and drilling specific energy for test data.

Correlation coefficient	Parameter relationship equation with drilling specific energy	Parameter	Equation
0.44	$DSE = 537.52 \times e^{-0.015\ DT}$	Pressure sonic log (Us/ft)	(20)
0.41	$DSE = 145.9 \times e^{-0.002\ DTs}$	Shear sonic log (Us/ft)	(21)
0.21	$DSE = 238.62 \times e^{-0.203\ NPHI}$	Porosity log (dec)	(22)

Table 5. General relationship between geo-mechanical parameters with drilling specific energy.

Correlation coefficient	Parameter relationship equation with drilling specific energy	Equation
0.79	$DSE = 124.38 \times \frac{e^{0.007\ UCS} \times e^{0.004\ PHI}}{e^{0.001\ FLOW}}$	(23)
0.81	$DSE=1255 \times \frac{e^{0.004\ UCS} \times e^{0.002\ PHI}}{e^{0.002\ FLOW} \times e^{0.032\ DT}}$	(24)

Table 6. Correlation coefficients and coefficients of determination of hybrid model geo-mechanical parameters of training data.

R	R. square	Adjusted R. square	Std. error of Estimation
0.79	0.63	0.63	21.70

Table 7. ANOVA hybrid model geo-mechanical parameters of training data.

Model	Sum of square	df	Mean square	F	Sig.
Regression	459448	3	153149	325.3	0.000
Residual	269273	572	470.7		
Total	728721	575			

Table 8. Regression multipliers analysis of hybrid model geo-mechanical parameters of training data.

	Unstandardized coefficient		Standardized coefficients	t	Sig.
	B	Std. error	Beta		
Constant	104.1	12.01		8.62	0.000
UCS	1.42	0.078	0.515	18.2	0.000
PHI	0.037	0.194	0.1	0.19	0.008
FLOW	–0.16	0.01	–0.42	–14.3	0.000

Of all the intended parameters, UCS, the rock internal friction angle, and the fluid flow remained in the equation, and the rest were removed due to the co-linearity and probability level of more than 0.05. In this equation, the relationship between DSE with the parameters of UCS and the internal friction angle of the rock was direct, and its relationship with the fluid flow parameter was reverse, which could be justified based on the earlier studies. It should be noted that due to the co-linearity of UCS with Young's modulus and the co-linearity of the adhesion with pore pressure, these two parameters were removed. The parameter Poisson's ratio was used in the equation but was then removed due to a low significance level.

4.3. Studying hybrid model of geo-mechanical parameters regarding DSE for test data

The final results of the regression analyses for the dependent variable of DSE and the independent variables of rock characteristics are provided in Table 9 for the test data. Equation (26) is the most appropriate hybrid model of the geo-mechanical parameters for predicting the drilling specific energy. The multiple correlation coefficient of the model was 0.83.

From the relationships presented in Table 9, equation (27) is the best one for the specific energy due to the high correlation coefficient. However, in the analysis of the F and T tests, it is disregarded with respect to the non-significance of the relationship. In this model, as the training data, UCS, the internal friction angle of the rock, and the fluid flow were the effective variables that appeared in the equation after removing the co-linearity and predicting the dependent variable. The F and T tests became significant as the model coefficients of equation (26). Tables of model pattern analysis, ANOVA, and regression coefficients are provided in Tables 10-12.

Table 9. General relationship geo-mechanical parameters with drilling specific energy.

Correlation coefficients	Parameter relationship equation with drilling specific energy	Equation
0.78	$DSE = 139 \times \frac{e^{0.005\ UCS} \times C^{0.0003}}{e^{0.005\ DT} \times Poisson^{0.103}}$	(25)
0.83	$DSE = 119 \times \frac{e^{0.006\ UCS} \times e^{0.001\ PHI}}{e^{0.0008\ FLOW}}$	(26)
0.85	$DSE = 110 \times \frac{e^{0.005\ UCS} \times e^{\ 0.001\ PHI}}{e^{0.0001\ FLOW} \times Poisson^{0.112}}$	(27)

Table 10. Correlation coefficients and coefficients of determination hybrid model geo-mechanical parameters of test data.

R	R. square	Adjusted R. square	Std. error of the estimation
0.83	0.70	0.70	13.27

Table 11. ANOVA hybrid model geo-mechanical parameters of test data.

Model	Sum of square	df	Mean square	F	Sig.
Regression	109071	3	36357	206	0.000
Residual	45836	260	176.3		
Total	154907	263			

Table 12. Regression multiplier analysis hybrid model geo-mechanical parameters of test data.

	Unstandardized coefficient		Standardized coefficients	t	Sig.
	B	Std. Error	Beta		
Constant	79.7	8.64		9.22	0.000
UCS	1.28	0.058	0.799	22.13	0.000
PHI	0.20	0.155	0.048	1.34	0.020
FLOW	–0.024	0.009	–0.091	–2.62	0.009

F-test or ANOVA are generalized forms of T-test, which is used for evaluate identical or non-identical for two societies or several societies. According to Table 11, the value for Sig. was calculated to be less than 0.05. Therefore, the null hypothesis that the multiple correlation compressive strength, internal friction angle, and fluid flow for predicting the amount of drilling specific energy is rejected. From all intended parameters of test data, UCS, the internal friction angle of the rock, and the fluid flow remained in the equation, and the rest were removed due to the co-linearity and probability level of more than 0.05. In this equation, the relation between DSE with UCS and the internal friction angle was direct, and the relationship between DSE and the flow rate parameter was reverse, which can be justified based on the earlier studies. Compressive strength is the most important geo-mechanical parameter affecting DSE due to the high beta factor. With regard to the same relations of specific energy and geo-mechanical parameters for the training and test data, it can be concluded that the relationship obtained is appropriately verified and validated, and equation (26) can be used to obtain DSE.

4.4. Validation of regression equation results

After regression analysis, we had to study the normal distribution of data. By studying the distribution of the remaining ones, we could determine the true and false hypotheses. The difference between the observed value and the value obtained by the equation is the residual value. To study normality, the regression normal diagram was examined. If residuals constitute a normal graph, dots must be located near the straight line. By studying the residual distribution, correctness of the hypotheses can be determined. The residuals obtained had to have the following characteristics:

- Distribution of the residuals must be normal, and its average error must be zero.

• There should be a constant variance for all values of independent variables.

• When the residuals are placed versus the predicted values, no special relationship should be observed. Thus to study and analyze the residuals, the charts drawn in Figures 3 and 4 were used. The results of these charts confirmed the normality of error, zero error mean, and constant variance of the error.

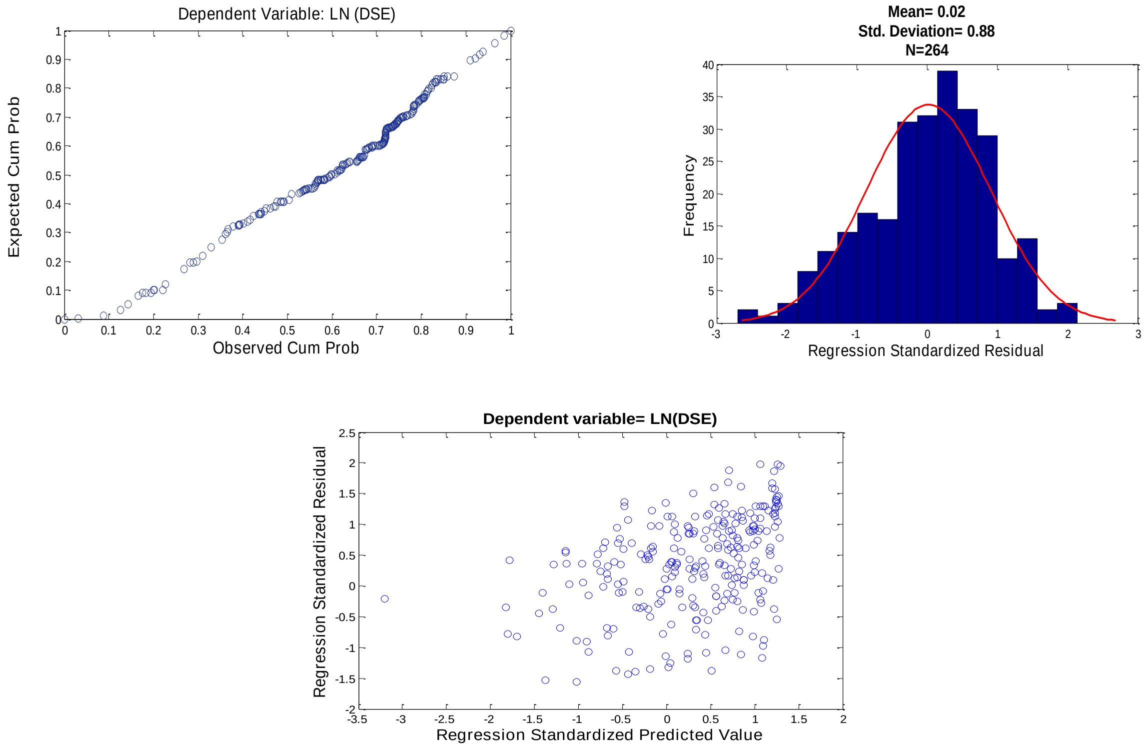

Figure 3. Residual analysis to predict drilling specific energy based on geo-mechanical parameters for test data.

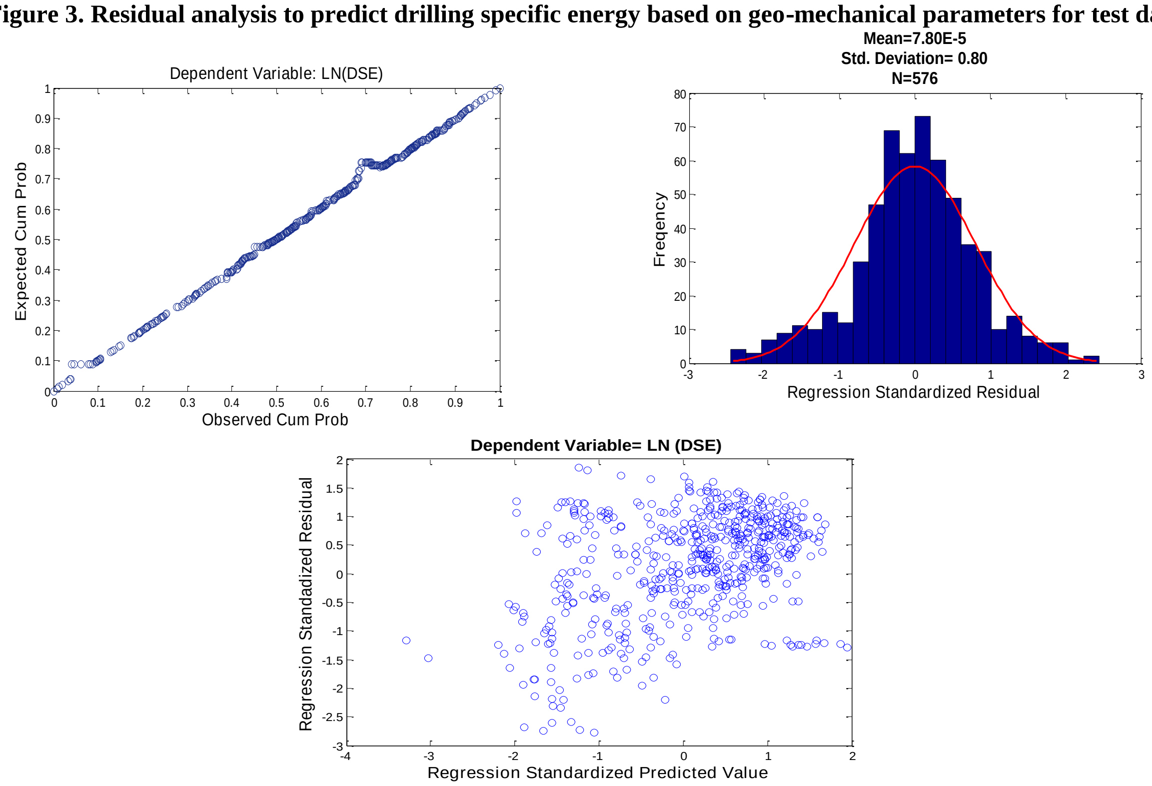

Figure 4. Residual analysis to predict drilling specific energy based on geo-mechanical parameters for train data.

5. Conclusions

Specific energy index can be used to predict the amount of energy used for drilling. To find the relationship between DSE and its effective parameters, the multivariate regression model was used. Modeling DSE was done using the multivariate regression, which contained the parameters rock characteristics, well logs, and a combination of these two features. After analyzing the model, the correlation coefficients obtained for the training and test data were, respectively, obtained to be 0.79 and 0.83.

With regard to the correlation coefficient of the relation obtained from the training data and equation validation with the test data, it can be concluded that the relation obtained has a high credibility,

and could be used to obtain the DSE parameter.

The parameters UCS, internal friction angle, and flow rate were among the most important factors affecting DSE. Increasing UCS and the internal friction angle leads to the increase in DSE. Increasing the flow rate can improve the transportation performance of cuttings, as well. As a result, the energy transfer between the drill bit and the rock can be done better, and less energy is required for drilling. It should be noted that excessive flow rate washes-off formation layers of the well.

Due to a high beta factor, the compressive strength is the most important geo-mechanical parameter affecting DSE. With regard to the similarity and co-linearity of most of the geo-mechanical parameters obtained, most of them were excluded from the model. It seems that more parameters of this type can be used regarding the rock mechanical tests and the direct obtaining of these parameters.

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چکیده:

تعدد فاکتورهای مؤثر در عملیات حفاری نشان‌دهنده پیچیدگی تقابل مته و سنگ است که وابستگی پارامترها و غیرخطی بودن روابط بین آن‌ها را به دنبال دارد. توده سنگ یا به عبارتی دیگر سازند مورد نظر حفاری به عنوان محیط حفاری نقشی بسیار اساسی در میزان سرعت حفاری، استهلاک مته، ماشین و هزینه‌های کلی حفاری دارد؛ بنابراین شناخت محیط حفاری و خصوصیات توده سنگ برجا کمک بسیار زیادی در انتخاب ماشین می‌کند. در این تحقیق ابتدا با جمع‌آوری اطلاعات زمین‌شناسی، نگاره‌های چاه، داده‌های حفاری، داده‌های مربوط به مغزه‌ها و اندازه‌گیری‌های فشار سیال سازند در چاه‌های مختلف، مدل ژئومکانیکی یک‌بعدی برای چاه‌های مورد مطالعه ساخته می‌شود. با داشتن پارامترهای حفاری هر قسمت از سازند، مقدار انرژی ویژه آن محاسبه می‌گردد. از شاخص انرژی ویژه می‌توان مقدار انرژی مصرف شده برای حفاری را پیش‌بینی کرد. به منظور یافتن رابطه بین انرژی ویژه حفاری و پارامترهای مؤثر بر آن از مدل رگرسیون چند متغیره استفاده گردید. مدل‌سازی انرژی ویژه حفاری توسط رگرسیون چند متغیره که شامل پارامترهای خصوصیات سنگ، نگاره‌های چاه پیمایی و تلفیقی از این دو ویژگی بوده ساخته شده است. ۷۰٪ داده‌ها به عنوان آموزش و ۳۰٪ داده‌ها، به عنوان تست برای اعتبار سنجی انتخاب شدند. پس از تحلیل و بررسی مدل، ضریب همبستگی‌های به دست آمده برای داده آموزش و تست به ترتیب ۰/۷۹، ۰/۸۳ گزارش گردید. پارامتر مقاومت فشاری تک محوری، زاویه اصطکاک داخلی و جریان سیال از جمله مهم‌ترین پارامترهای مؤثر بر انرژی ویژه حفاری شناخته شدند.

کلمات کلیدی: انرژی ویژه حفاری، رگرسیون چند متغیره، خصوصیات ژئومکانیکی، نگاره‌های چاه پیمایی.