



Quantification of Rock Strength Using the Mechanical Drilling Parameters

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Abstract. The estimation of rock strength is most often required for the preliminary stage of rock engineering projects. The determination of rock strength properties in the laboratory is reliable, but the availability of a number of fine quality core samples for lab testing is very difficult. In this study, an attempt is made to investigate the usability of variations of thrust developed at the rock-bit interface and vibration frequency generated in the drilling machine head for estimation of rock strength during the rotary drilling. The variation of thrust and vibration frequency during drilling is measured using sophisticated digital type drilling dynamometer and data acquisition system (DAQ) with accelerometer sensor respectively. The second order regression models were developed to predict the rock strength such as uniaxial compressive strength considering the machine operating parameters and measured variables. The evaluation of the prediction ability of the developed models was checked using the three performance indices known as VAF, RMSE, and MAPE. The results revealed that the approached method is highly efficient for estimation of rock strength during rotary drilling.

Keywords: Uniaxial compressive strength · Vibration signal · Vibration frequency · FFT · Frequency domain · Drilling dynamometer

1 Introduction

Rock mechanics deals with the study of mechanical and physical properties of rocks. The vital mechanical property of rocks such as a uniaxial compressive strength (UCS) is often used in many engineering projects concerned with a rock engineering background [1]. The determination of UCS in the laboratory is reliable, but it is expensive, time-consuming and often high-quality core specimens are needed for the test [2]. It is not always possible to obtain a sufficient amount of fine quality drilled cores from weak, highly fractured, weathered and thin layers of rock matrix [3]. Therefore, the engineers and geologists have been attracted to quantify the rock strength indirectly through the use of predictive empirical models [4]. Some of the indirect tests such as point load, Schmidt hammer, and p-wave velocity tests are often

used to estimate rock strength [5–7]. However, the standard samples for the indirect test may not always be possible for weak or soft rocks such as sedimentary rock type. Recently, the quantification of rock properties during the drilling was investigated by many researchers with acceptable level errors. The mechanical drilling parameters such as bit diameter, bit speed, weight on bit and corresponding penetration rate, sound level and many more physical parameters have been used to correlate with various rock properties. From the earlier investigation on the characterization of rocks, estimation of rock properties during drilling is found easy, less time consuming and also economical as no core samples of rocks are required. The mechanical drilling parameters like bit load or thrust, speed and penetration rate of diamond drill bit have a strong relationship with rock mass strength [8]. Finfinger et al. [9] attempted to identify the properties of overlying rocks in underground mines during rock bolting operation. It was observed that there is considerable variation of thrust and torque as the drill bit moves to different rock layers. Stuart et al. [10] proposed a method for quantification of formation properties around an oil well by analyzing the acoustic waves generated at the bottom hole assembly of drill unit. An investigation on sound level produced during the drilling of different rocks using a portable pneumatic drilling machine was made by Vardhan et al. [11]. The results revealed that the sound level linearly increases as the UCS of rocks increases. Kumar et al. [12] attempted to predict the uniaxial compressive strength, tensile strength and porosity of sedimentary rocks using sound level produced during rotary drilling. The prediction mathematical model for each property was developed using the drilling parameters and equivalent sound level. It was observed that the sound level produced during drilling was increased as the UCS of rocks increases and the sound level was decreased as the porosity of rocks increases. The evaluation of the prediction model concluded that the equations would be useful for the preliminary stage of mining engineering design projects. Yari and Bagherpour [13, 14] have conducted the experimental investigation to estimate the geomechanical properties of igneous rocks as well as sedimentary rocks using the five dominant frequency of an acoustic signal acquired during rotary drilling. The dominant frequency was extracted from the time domain acoustic signal using Fast Fourier transformation (FFT). The results revealed that the fourth dominant frequency is capable of predicting the UCS and tensile strength with a high coefficient of determination value. The study on identification of rocks based on acoustic signal parameter gathered while drilling was made by the Zborovjan et al. [15]. The results revealed that the analysis of the frequency component of the acoustic signal is useful for identification of rock type and controlling the rock disintegration process. Lakshminarayana et al. [16] attempted to predict some physico-mechanical properties of sedimentary rocks using the drilling parameter and the maximum or sometimes referred as dominant frequency of vibration induced at spindle head of conventional rotary drilling machine. It was observed that the vibration frequency at spindle head was increased as the properties of rocks such as uniaxial compressive strength and tensile strength increases during the drilling. During drilling, an attempt was made by Rostami et al. [17] to detect the voids in rocks using the vibration data acquired at the drill head. It was observed that the amplitude of vibration would be less when the drill bit enters into the porous region of rocks.

In this study, an attempt is made to estimate the UCS of sedimentary rocks using the machine operating parameters (penetration rate, bit dia, bit speed) and the

mechanical data measured during the rotary drilling such as thrust or weight on the bit and vibration frequency of machine head. The different amount of thrusts acting on the bit during drilling was measured by dynamometer and the vibration parameter was measured using the data acquisition system (DAQ).

2 Experimental Investigation

The experiment was conducted using the sedimentary rock samples such as shale, sandstone and limestone. The samples were directly collected from the field. The rock specimens were prepared by cutting off the rock samples into a cubic block of size 15 cm × 15 cm × 15 cm. While collecting the rock samples, a proper inspection was carried out for macroscopic defects such as fractures and joints.

2.1 Experimental Setup

In this experiment, a heavy duty BMV 45 T20 computerized numerical control (CNC) vertical machining center was used for drilling the rock samples as shown in Fig. 1. The thrust and torque variations of the drill bit during the drilling of each type of rock sample were measured using the drill tool dynamometer. Similarly, the vibration frequency of the machine head was measured using the vibration data acquisition system (DAQ). The drilling operation was done using the diamond core drill bits of uniform shank length 30 mm and diameter of 12 and 16 mm. The different drilling operational parameters such as rotational speed of bit and penetration rate were set in the CNC machine by numerical control (NC) programming method.

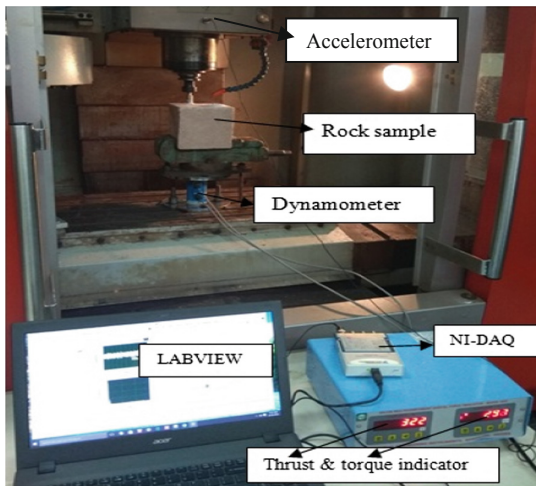


Fig. 1. Experimental setup

Drilling Dynamometer

During the drilling of different rocks, the amount of thrust acting and torque developed at the bit-rock interface were measured using the sophisticated drilling dynamometer. The measuring range of thrust in the dynamometer was 0 ± 5000 N and the measuring range for the torque was 0 ± 50 N-m. Basically, the dynamometer consists of a cylinder fitted with steel plates at both ends. The bottom plate can be fixed to t-slots of machine table using bolt and nut. Similarly, the machine vice used for holding the rock sample can be fixed directly to the top plate of dynamometer using suitable bolt and nuts. The analog output from the dynamometer is connected to the digital indicator of dynamometer which shows the numerical value of thrust and torque.

Measurement of Vibration Frequency of the Machine Head During Drilling

The vibration frequency of the CNC machine head was measured using the sound/vibration data acquisition system (DAQ). The DAQ system basically consists of DAQ hardware, IEPE accelerometer and LabVIEW application software. The NI-9234 model DAQ hardware was used for converting the analog signal into a digital type. The important specification of DAQ hardware is as follows

- Number of the channel - 4
- ADC resolution - 24 bits
- Sampling rate -1.652 Ks/s to 51.2 Ks/s.
- Frequency - 13.1072 MHz

The mounting of an integrated electronic piezo-eclectic (IEPE) accelerometer on the machine head using the magnetic type mount is shown in Fig. 1. The specification of IEPE accelerometer as follows.

- Model: YMC121A10 IEPE
- Sensitivity: 9.81 Mv/g

Initially, the accelerometer is fixed on the machine head using the magnetic mount. The output from the accelerometer is connected to DAQ hardware using the single-ended BNC connector. The DAQ is a signal conditioning device which converts the analog signal captured from the accelerometer into a digital signal. The digital signal coming out from the DAQ hardware is in turn connected to laptop installed with LabVIEW application software. The application software process the signal and representing the vibration data in the time domain as shown in Fig. 2. The maximum vibration frequency (Z) or dominant frequency is usually meant the one that carries more energy with respect to all the other frequencies in the considered spectrum. The example of dominant frequency at which the machine head ($Z = 327$ Hz) was vibrating for a particular operating parameter during the drilling of shale is shown in Fig. 3. The extraction of frequency data from the time domain vibration signal was achieved using the Fast Fourier transformation (FFT) graphical program in LabVIEW application software.

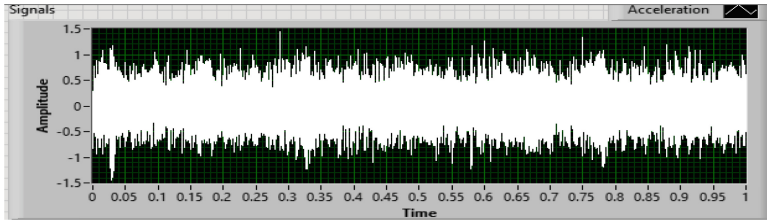


Fig. 2. Time domain signal

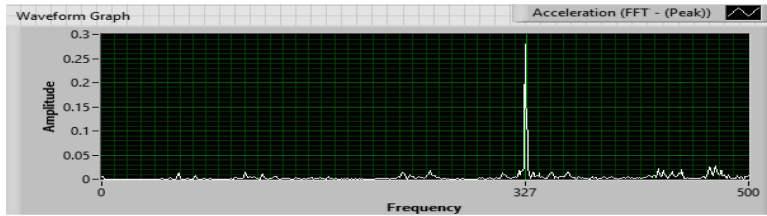


Fig. 3. Frequency domain signal

3 Methodology

3.1 Determination of Thrust, Torque and Vibration Frequency

During the drilling of different sedimentary rocks using the CNC vertical machining center, the variations of thrust acting and torque developed at the bit-rock interface, and the variations of vibration frequency at the machine head were recorded. The standardized cubical rock sample of size 15 cm × 15 cm × 15 cm was tightly fixed in the CNC machine vice. The different machine operational parameters such as drill bit diameter, drill bit speed, and penetration rate were used for drilling the rock samples. For each rock type, a total of 32 holes having a constant depth of 50 mm are drilled using the 32 (2 drill bit dia × 4 drill bit speed × 4 penetration rate) combinations of machine operational parameters (12 and 16 mm drill bit, 400, 500, 600 and 700 r.p.m drill bit speed and a penetration rate of 2, 3, 4 and 5 mm/min). During the drilling for a particular machine operational parameter, the numerical value of thrust was continuously varying as the drill bit was advancing through a 50 mm depth hole. As the drill bit is moving to 10, 20, 30, 40 and 50 mm depth, the corresponding reading of five thrust values were taken down at those depths using the digital indicators of the dynamometer. Later, the arithmetic average of five thrust was calculated for a particular machine operating condition. Similarly, the vibration signal of 1 s having 5 iterations emanated from the machine head was captured and its corresponding vibration frequency was noted down at the same mentioned depths using the frequency domain data in LabVIEW application software. But the vibration frequency captured five times for a particular operating condition was found almost consistent.

The direct measurement of UCS is measured in well-established rock mechanics laboratory. The uniaxial compressive strength of different sedimentary rocks was

measured using the micro-controlled type AIM-317E-MU compression testing machine. An NX size specimen having a diameter of 54 mm and a length of 135 mm were prepared and the UCS of rock specimen was determined as per the guidelines suggested by ISRM. Before testing the specimen for UCS the specimen was completely dried using an electric oven. At least three specimens were used for testing the UCS. The arithmetic mean of all three rock specimen was considered for analysis purpose.

4 Results and Discussion

In the current experiment, a total of 192 data (6 rock types \times 32 test conditions) of each measured parameters i.e., thrust and vibration frequency is acquired during the rotary drilling. For developing the multiple regression models, the thrust and vibration frequency is used along with the machine operational parameters. The maximum and minimum values of measured variables which are selected from the 32 data set of each rock sample are summarized in Table 1. During the drilling process, the variation in thrust and vibration frequency is affected by so many factors in a complex way. Therefore, a detailed process is defined by second-order multiple regression models. The analysis of variance (ANOVA) was carried out in order to know which variable is significantly influencing the response. The considered responses are UCS and BTS. The machine operational parameters are identified as drill bit diameter (D) in mm, drill bit speed(S) in r.p.m and penetration rate (PR) in mm/min. Similarly, the measured variables which are varying due to machine operational parameters and rock properties are thrust (T) in Newton and vibration frequency (Z) in Hertz.

Table 1. Mechanical rock properties and range of measured variables during drilling

Rock sample	UCS (Mpa)	BTS (Mpa)	Thrust (N)		Vibration frequency (Hz)	
			min	max	min	max
Shale	19.6	2.3	315	635	327	626
Sandstone-1	37.5	3.4	397	802	330	629
Sandstone-2	63.8	4.1	495	1009	337	642
Limestone-1	93.1	7.5	567	1130	340	656
Limestone-2	119	8.1	617	1207	342	667
Limestone-3	142.6	10.2	672	1315	345	669

The variations of selected measured variables (thrust and vibration frequency) are the function of machine operating parameters and mechanical properties of rocks. The mathematical model for establishing the relationship between rock properties and considered variables can be written as $y = f(x_1, x_2, x_3, x_4, x_5) + \psi$ where y is the response and x_1, x_2, x_3, x_4, x_5 are the machine operational parameter and measured variables, and ψ is fitting error. In general, the second order model can be represented as follows

$$f = a_o + \sum_{i=1}^n a_i x_i + \sum_{i=1}^n a_{ij} x_i^2 + \sum_{i < j}^n a_{ij} x_i x_j + \psi \tag{1}$$

where, a_i represents the linear effect of x_i , a_{ij} represents the quadratic effect of x_i , and a_{ij} in fourth term represents the interaction effect produced due to the linear interaction of x_i and x_j . In developing the multiple regression models, the backward elimination method was used as a screening technique. In ANOVA table, if absolute t value of an independent variable was not greater than the tabulated t value at 95% confidence level, then that particular independent variable was removed and the multiple regression procedure was continued using the remaining independent variables. The procedure is repeated until the remaining independent variables could not be removed from the model and that corresponding generated regression model was selected.

4.1 Prediction of Uniaxial Compressive Strength

The best prediction model developed for uniaxial compressive strength is:

$$UCS = 77.4 - 31.60 \times PR - 2.151 \times S - 3.745 \times D + 0.1787 \times T + 2.861 \times Z + 2.698 \times PR^2 - 0.000804 \times Z^2 + 0.01823 \times PR \times S - 0.01616 \times PR \times T \tag{2}$$

The Eq. (2) represents the best second-order multiple regression model developed for prediction of UCS. From Table 2 it was concluded that the developed model explains 93.60% of the total variation in the observed UCS. The significance of regression coefficients are illustrated in Table 3. In this, the value of p for all the terms are statistically significant at $p < 0.05$ for 95% confidence level and also the calculated absolute t values are much higher than the tabulated t values (for 95% confidence level and 9 degrees of freedom, for $k = n - 1$, $t = 1.860$). It is therefore concluded that all the terms generated in the selected regression model are significantly influencing the UCS. The influence of linear, square and interaction terms of the regression model is explained in ANOVA Table 4. The linear terms are significantly influencing the UCS. The calculated F value is sufficiently greater than the tabulated F value of 3.36 to explain the adequacy of the developed model. Figure 4 indicates the comparison of the UCS of rocks measured in the laboratory and the UCS predicted using the prediction model. The predicted values are very close to the measured values. So that it is concluded that the developed models are highly efficient.

Table 2. Model summary for UCS

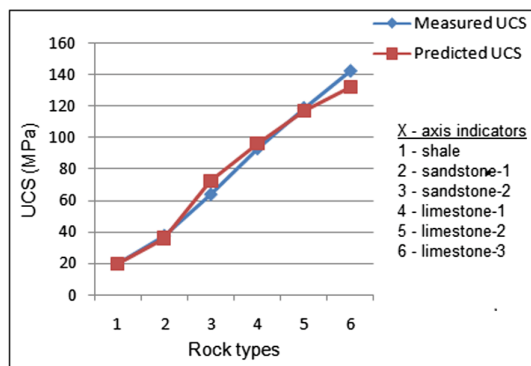
R ²	Adjusted R ²	Predicted R ²	Standard error
93.60	93.28	92.89	11.29

Table 3. Regression coefficients and their significance

Predictors	Regression coefficients	T-value	p-value
Constant	77.4	2.66	0.008
PR	-31.60	-4.60	0.000
S	-2.151	-14.27	0.000
D	-3.745	-8.97	0.000
T	0.1787	7.96	0.000
Z	2.861	9.59	0.000
PR ²	2.698	3.03	0.003
Z ²	-0.000804	-5.14	0.000
PR × S	0.01823	2.72	0.007
PR × T	-0.01616	-3.57	0.000

Table 4. ANOVA (UCS)

Source of variations	DF	Adj SS	Adj MS	F-value	p-value
Model	9	339185	37687.3	516.66	0.000
Linear	5	58788	11757.4	460.9	0.000
Square	2	4553	2276.45	35.69	0.000
Interaction	2	2560	1279.75	20.07	0.000
Error	182	23214	127.6	–	–
Total	191	362400	–	–	–

**Fig. 4.** Comparison of measured and predicted UCS

4.2 Evaluation of Prediction Performance of the Developed Model

In the present study, the efficiency or prediction capacity of the developed models are investigated using the three indices known as variance account for (VAF), root mean square error (RMSE) and mean absolute percentage error (MAPE).

$$VAF = \left[1 - \frac{\text{var}(m - p)}{\text{var}(m)} \right] \times 100 \quad (3)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (m - p)^2} \quad (4)$$

$$MAPE = \frac{1}{N} \sum_{i=1}^N \left| \frac{(m - p)}{m} \right| \times 100 \quad (5)$$

In Eqs. (3)–(5), ‘m’ and ‘p’ are representing the UCS measured in the laboratory and the UCS obtained using the predictive model respectively. Similarly, the N represents the number of data used. The model would predict the response with zero errors if the VAF and RMSE values are 100 and 0 respectively. The MAPE indicates the absolute percentage error or accuracy of the model in terms of percentage. The values of VAF, RMSE, and MAPE for the developed models are tabulated in Table 5.

Table 5. Indices of prediction capacity of the derived models

Dependent variable	Indices of performance		
	VAF (%)	RMSE (Dependent variable units)	MAPE (%)
UCS (Mpa)	93.60	10.99	15.09

5 Conclusions

In this experimental investigation, the machine operating parameters along with the measured variables such as thrust developed at bit-rock interface and vibration frequency induced at machine head during the rotary drilling were used to predict some of the mechanical properties of sedimentary rocks. For rock drilling, the CNC vertical milling centre with different penetration rate, speed and drill bit diameter was used as the machine operational parameters. The thrust and vibration frequency was measured for all machine operating conditions and the same was used for developing the prediction models.

- It was observed that the thrust developed at the bit-rock interface was significantly increased as the UCS of rocks increases during the drilling.
- The vibration frequency was moderately changed as UCS of rocks increased.
- The evaluation of the prediction performance of the developed model indicated that the predictive models are well efficient to predict the UCS of sedimentary rocks with an acceptable level error.
- Therefore, it was concluded that the suggested approach can be successfully used for preliminary investigation of UCS which is often used as a primary data for the design of mining and civil engineering projects.

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