Rock Mech. Rock Engng. (2003) 36 (4), 323–332
DOI 10.1007/s00603-003-0002-3

Rock Mechanics and Rock Engineering
Printed in Austria

Technical Note

Estimation of Penetration Rate in Percussive Drilling by Means of Coarseness Index and Mean Particle Size

By

R. Altındağ

Department of Mining Engineering, Süleyman Demirel University, Isparta, Turkey

Received May 6, 2002; accepted January 23, 2003
Published online June 17, 2003

Keywords: Penetration rate, drillability, coarseness index, mean particle size.

1. Introduction

One of the most important problems of any drilling job is to predict the performance of rock drills during the operation. Drillability of a rock is usually defined by a set of parameters related to the drilling rate and the bit wear of the drilling rig. These parameters can be separated into 3 main categories as geomechanical parameters (foliations, discontinuities, etc.), machine parameters (rotation, thrust force, flushing, etc.) and operating process (drilling method, operation and maintenance of machine) (see Fig. 1).

Obviously, the geomechanical parameters, which influence the drilling performance and the bit wear, can not be altered. On the other hand, the machine parameters and operating parameters can be affected by various ways.

The relationships between the drillability and the rock properties have been investigated by many researchers (Teale, 1965; Miller, 1972; Pathinkar and Misra, 1976; Protodyakonov, 1962; Paone et al., 1969; Tandanand and Unger, 1975; Rabia and Brook, 1980; Miranda and Mello-Mendes, 1983; Howarth and Rowland, 1987; Bilgin et al., 1993 and Kahraman et al., 2000). These studies showed that any single parameter is not enough to define the drillability of a rock, therefore a combination of parameters has to be used.

Rabia (1980) determined surface area and rock impact hardness number from the results of percussive drill cuttings that failed to give correlation with the drill

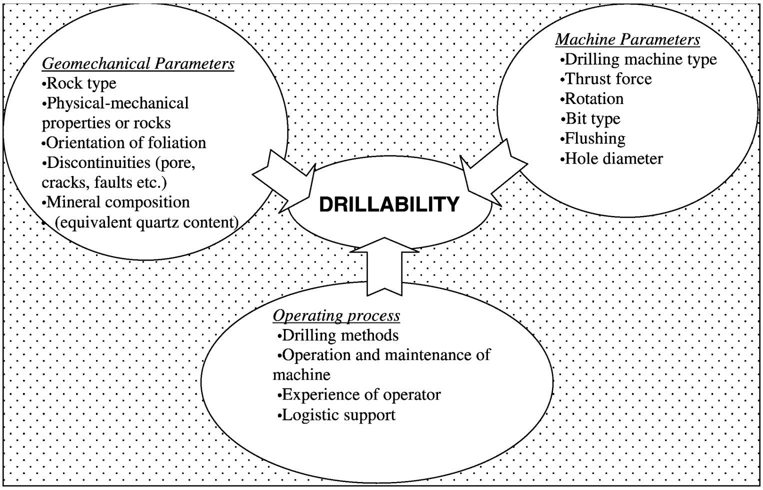

Fig. 1. The main factors affecting the drillability of a rock

variables. Pfleider and Blake (1953) concluded that a rough correlation exists between penetration rate and size range of cuttings, i.e. the higher the penetration rate, the coarser the particle size. Ersoy and Waller (1997) found that the wear rate of bits depends upon the particle size produced during drilling. The longer size, the faster is the wear.

In this study, the relationships between 3 parameters (the coarseness index (CI), mean particle size (d) and specific surface area (SSA)) determined at the laboratory and penetration rate (PR) determined at a limestone quarry have been investigated.

To predict the penetration rate of percussive drilling, by means of the coarseness index and mean particle size several dependable regressions have been developed using data obtained from 19 blastholes.

2. Experimental Studies

2.1 Field Studies

In drilling operations, the Atlas Copco ROC-F7 drilling rig was used. The drilling parameters of the machine are:

Drilling pressure: 150–210 kPa ($\times$ 100),
Air pressure: 7–8 kPa ($\times$ 100),
Rotation: 86 rpm,
Hole diameter: 115 mm.

The drilling performance is measured as penetration rate of a blasthole. During the drilling of each blasthole, net drilling time and penetration depths were recorded. The penetration depth values were taken from digital panels of the drilling unit. The net drilling time was measured by using a chronometer. The penetration rate (PR) was

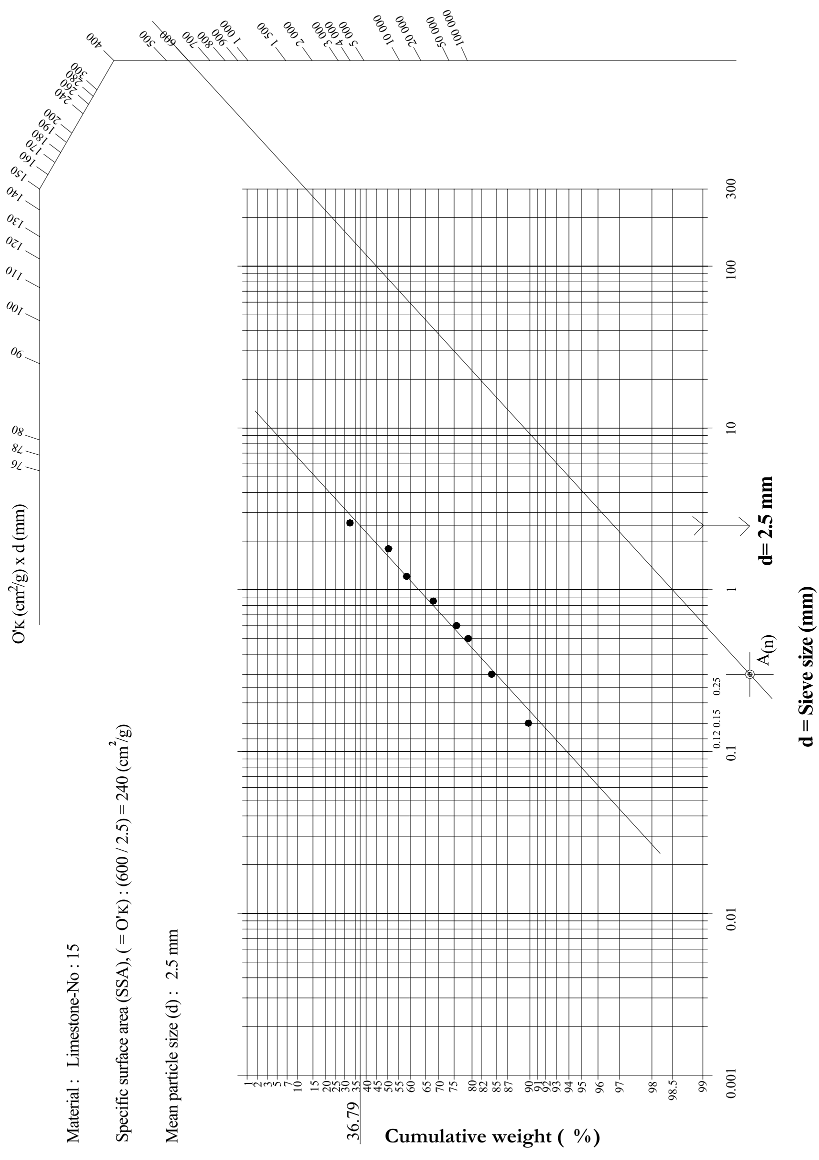

Fig. 2. The determination of mean particle size (*d*) and specific surface area (SSA) by RRS graph

calculated by using Eq. (1). The penetration rate values for all blastholes are given in Table 3. All blast hole measurements were done in the same region of the limestone quarry.

$$\text{Penetration Rate (PR)} = \frac{\text{Blasthole depth}}{\text{Net drilling time}}\left[\frac{\text{m}}{\text{min}}\right]. \tag{1}$$

In order to make sieve analysis in the laboratory, drill cuttings from different parts of blasthole were carefully collected. Approximately a 3 kg of rock chips from each blasthole was used for the sieve analysis. The drilling variables (e.g. operating pressure, rotation speed) were kept constant and recorded during the study.

2.2 Laboratory Studies

The rock chips taken from each blasthole were sieved by a series of sieve sizes (2.8–1.7–1.18–0.850–0.600–0.500–0.300–0.150 mm). The Rosin-Rammer-Sperling (RRS) graphs between size fraction and cumulative weight (%) were plotted according to data of sieve analysis (Fig. 2). The mean particle sizes (*d*) and the specific surface areas (SSA) of each sample were determined in the RRS graph (Aytekin, 1979). The results of the mean particle size and the specific surface area values for all blastholes are listed in Table 3.

2.2.1 Physical and Mechanical Properties

The physical and mechanical properties of limestone were determined by the recommended methods of International Society of Rock Mechanics (ISRM, 1981). The test results are summarised in Table 1.

2.2.2 Coarseness Index (CI)

The coarseness index is a non-dimensional number (Roxborough and Rispin, 1972). This index is derived using the sum of cumulative weight percentages of a particular size. The calculation is shown in Table 2. The determined coarseness index values of the all blastholes are given in Table 3.

In this analysis, the coarseness index (CI) is 638.13.

Table 1. Physical and mechanical properties of limestone

Rock properties		
Uniaxial comprehensive strength	(MPa)	93.6
Point load strength (Is_{50})	(MPa)	5.2
Density	(g/cm^3)	2.71
Schmidt Hammer value	(↓ L-Type)	42.8

Table 2. The sieve analyses of No.15 blasthole of limestone

Size (mm)	Weight (%)	Cumulative weight (%)
+ 2.8	33.17	33.17
− 2.8 + 1.7	16.96	50.13
− 1.7 + 1.18	8.85	58.98
− 1.18 + 0.850	8.35	67.33
− 0.850 + 0.600	8.28	75.61
− 0.600 + 0.500	2.88	78.49
− 0.500 + 0.300	5.94	84.43
− 0.300 + 0.150	5.56	89.99
− 0.150	10.01	100.00
Σ	100.00	
Coarseness Index (CI)		Σ = 638.13

Table 3. The analysis values of all blastholes of limestone

No. of blasthole	Location	Coarseness index (CI)	Penetration rate (PR) (m/min)	Mean particle size (d) (mm)	Specific surface area (SSA) (cm^2/g)
1	Isparta	624.37	2.10	2.8	625.0
2	Isparta	608.46	2.02	2.6	576.9
3	Isparta	473.16	1.14	1.1	1590.9
4	Isparta	581.07	1.62	1.8	388.9
5	Isparta	602.71	1.89	2.75	545.5
6	Isparta	555.80	1.44	2.2	1181.8
7	Isparta	532.85	1.36	1.5	866.7
8	Isparta	517.85	1.27	1.45	965.5
9	Isparta	606.13	1.80	2.5	520.0
10	Isparta	496.81	1.66	1.2	583.3
11	Isparta	506.54	1.18	1.4	1178.6
12	Isparta	570.11	1.62	2.45	816.3
13	Isparta	503.19	1.43	1.5	1733.3
14	Isparta	570.45	1.46	2.2	909.1
15	Isparta	638.13	1.77	2.5	240.0
16	Isparta	568.08	1.77	1.8	500.0
17	Isparta	626.20	1.99	2.4	291.7
18	Isparta	619.99	2.30	2.8	571.4
19	Isparta	606.58	1.69	2.0	400.0

3. Statistical Analysis

The penetration rates were correlated with the coarseness index, the mean particle size and the specific surface area by using the method of least square regression. The equation of the best-fit line, the 95% confidence limits, and the correlation coefficient (r) were determined for each regression.

Reliable relationships between penetration rate, coarseness index and mean particle size were found (Figs. 3 and 4). The relations can be expressed as Eqs. (2) and (3).

$$\mathrm{PR} = 0.257\,\mathrm{e}^{0.0032\,(\mathrm{CI})}, r = 0.84. \quad (2)$$

$$\mathrm{PR} = 0.9185\,\mathrm{e}^{0.2795\,(d)}, r = 0.81. \quad (3)$$

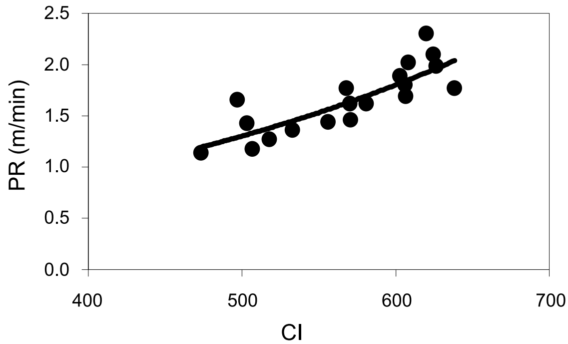

Fig. 3. Relationship between coarseness index and penetration rate

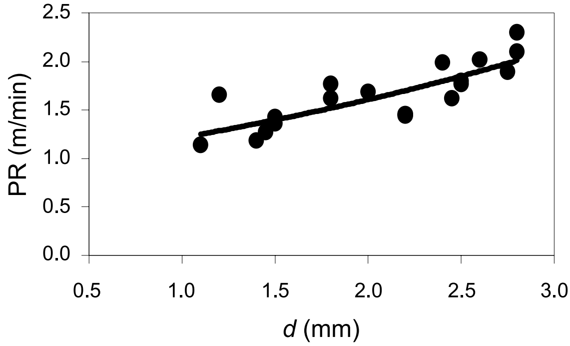

Fig. 4. Relationship between mean particle size and penetration rate

where PR is the penetration rate (m/min), CI is the coarseness index and d is the mean particle size (mm). This regression indicates that the penetration rate increases with increasing coarseness index and mean particle size.

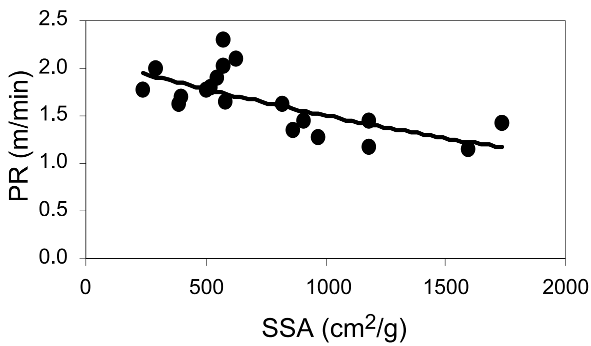

Fig. 5. Relationship between specific surface area and penetration rate

A non-linear relationship between penetration rate and specific surface area was obtained (Fig. 5). The relationship is given below (Eq. (4)).

$$PR = 2.1139\, e^{-0.0003\ (SSA)}, r = 0.73, \tag{4}$$

where PR is the penetration rate (m/min) and SSA is the specific surface area (cm^2/g).

The relationships between penetration rate and coarseness index with mean particle size were investigated by multi-regression analysis. The coarseness index and the mean particle size were evaluated as independent variables. The regression equation is:

$$PR_e = 0.00325\ (CI) + 0.193\ (d) - 0.583, r = 0.84, \tag{5}$$

where PR_e is the estimated penetration rate (m/min), CI is the coarseness index and d is the mean particle size (mm). Measured values of independent variables replaced into the regression formulas and estimated values of dependent variables have been calculated. Then, these estimated values of dependent variables were then plotted against its measured values (see Figs. 6–9). To evaluate these regressions, the measured values are compared with the corresponding regression estimates. For this,

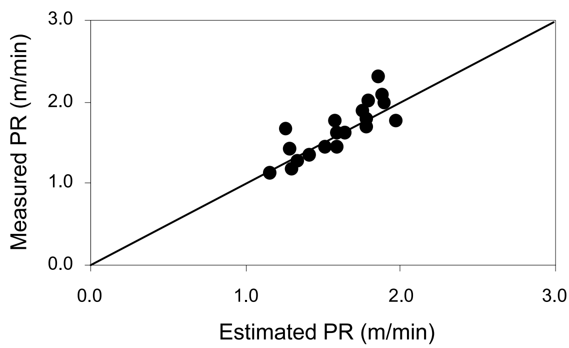

Fig. 6. Estimated PR vs. measured PR for coarseness index

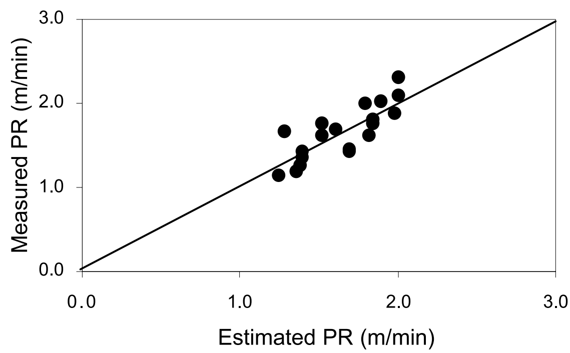

Fig. 7. Estimated PR vs. measured PR for mean particle size

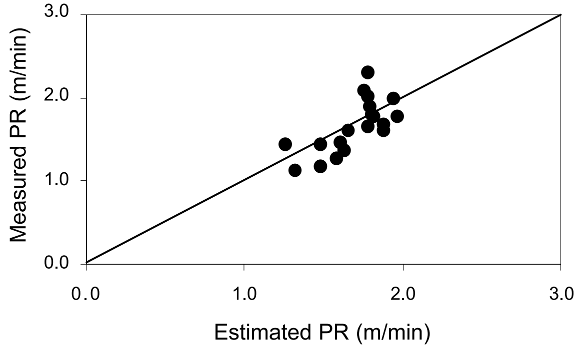

Fig. 8. Estimated PR vs. measured PR for specific surface area

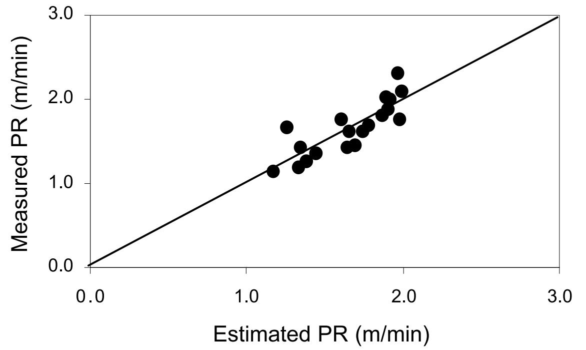

Fig. 9. Estimated PR vs. measured PR for multi-regression analysis (according to Eq. (5))

since, measured and estimated values are the measure of the same property, departure from 1:1 diagonal line indicates the discrepancy between these two sets of values. In case of error-free estimates, data points will lie on 1:1 diagonal line. Result of this plotting check indicates very good fits, i.e. the measured PR value and their regression estimates are very close.

4. Conclusions

It is well recognised that predicting the penetration rate and controlling the drilling process is very important for Rock Engineers. In order to estimate PR, in this study, the relationships between the penetration rates obtained from nineteen blastholes in a limestone quarry and 3 laboratory determined parameters have been investigated. The rock chips representing each blasthole were taken and sieved by using a series of sieves. The coarseness index, specific surface area and mean particle size were calculated from the data of sieve analysis for each blasthole.

There is a strong non-linear relation between penetration rate and coarseness index. An inverse exponential relation between penetration rate and specific surface area was found. Penetration rate decreases exponentially with an increase in specific surface area.

A significant exponential regression exists between penetration rate and mean particle size. High mean particle size value indicates higher penetration rate in percussive drilling process. This means that the most of the energy spent in drilling is expended to fracture the rock into chips. The penetration rates of the blastholes can be estimated by using the coarseness index and mean particle size of the rock.

Further study is required to see whether similar relationships can be found with other rock types.

Acknowledgement

This research was partly supported by SDU Research Foundation (RF) Project (Project No: AF-396). The author would like to thank SDU – RF for granting its permission to publish this research.

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Author's address: Dr. Raşit Altındağ, Süleyman Demirel Üniversitesi, Mühendislik Mümarlık Fakültesi, Maden Mühendisliği Bölümü, 32260 Isparta, Turkey. E-mail: rasit@mmf.sdu.edu.tr