1a" International Mining Congress and Exhibition ot Turkey-IMCET 2003, # 2003, ISBN 975-395-605-3

Drillability Prediction in Rotary Blast Hole Drilling

N. Bilgin
Mining Engineering Department, Istanbul Technical University, 80626 Maslak, Turkey
S. Kahraman
Geological Engineering Department, University ofNigde, 51100 Nigde, Turkey

ABSTRACT: Rotary blast hole drills were observed in fourteen rock types at eight open pit mines. The net penetration rates of the drills were calculated from the performance measurements. Rock samples were collected from the drilling locations and the physical and mechanical properties of the rocks were determined both in the field and in the laboratory. Then, the penetration rates were correlated with the rock properties and regression equations were developed. The uniaxial compressive strength, the point load strength, Schmidt hammer value, cerchar hardness and impact strength show strong correlations with the penetration rate. The equations derived from Schmidt hammer and impact strength values are valid for the rocks having uniaxial compressive strength over 25 MPa. The Brazilian tensile strength and cone indenter hardness exhibit quiet good correlations with the penetration rate. Concluding remark is that, the point load, the Schmidt hammer and the impact strength test which are easier tests to carry out can be used for the rapid estimation of the penetration rate of rotary blast hole drills.

I INTRODUCTION

Rotary blast hole drills have been extensively used in open pit mines for overburden removal. The penetration rate is generally accepted to be one of the most important parameter in mine planning and cost estimation.

The drillability of the rocks depends not only on Hie rock characteristics, but also on the drilling tools, as well as operational variables. On the rotary drilling, rotational speed, thrust, torque and flushing are the operational variables, known as the controllable parameters. Rock properties and geological conditions are the uncontrollable parameters. Although, many attempts have been made to correlate the drillability with the rock properties, the rock characteristics affecting rotary drilling have not been completely defined. In this study, rock properties were correlated with the penetration rates of the rotary blast hole drills using the data from Eskikaya & Bilgin (1993) and Kahraman (1997).

2 PREVIOUS INVESTIGATIONS IN ROTARY DRILLING

Many investigators have tried to correlate rotary drilling rate and various mechanical rock properties and developed penetration rate models. Rollow (1962) presented an estimation chart for the prediction of penetration rate of rotary drills. The chart can be used by the microbit drilling test. Fish (1968) performed a model for rotary drills that penetration rate is directly proportional with thrust and inversely proportional with uniaxial compressive strength. Morris (1969) conducted penetration tests using a tungsten carbide compact and defined a drillability index, which is the ratio of crater depth to threshold force. He developed a penetration rate model using this drillability index. Singh (1969) showed that compressive strength is not directly related to the drilling rate of a drag bit. Clark (1979) stated that drilling strength, hardness and triaxial strength of rock exhibited reliable correlations with drilling efficiency. Warren (1981) developed a penetration rate model for application to tri-cone rotary bits in soft rock formations. The model relates the weight on the bit, rotary speed, bit size, bit type and rock strength to penetration rate. Miranda & Mello-Mendes (1983) presented a rock drillability definition based on Vicker's microhardness and specific energy. Adamson (1984) showed a close correlation between a quantitative measure of rock texture, the texture coefficient, and penetration rate of rotary drill. Karpuz et al. (1990) developed regression models for the prediction of penetration rates of rotary tri-cone and drag bits. They also proposed a chart for the prediction of penetration rate, as well as thrust and rotational speed values. In their study, the uniaxial compressive strength has been determined as the dominant rock property. Pandey et al. (1991) correlated the penetration rate value obtained from microbit drilling test with compressive strength, tensile strength, shear strength and Protodyakonov Index and found logarithmic relationships. Wijk (1991) derived a penetration rate model lor rotary drilling. He used the Stamp Test strength index previously described by him in the model. Bilgin et al. (1993) developed a mathematical model of predicting the drilling rate of rotary blast hole drills using the drillability index obtained from the indentation tests. Reddish & Yasar (1996) developed a new portable rock strength index test based on specific energy of rotary drilling. Kahraman (I999) performed regression analysis and developed penetration rate models lor rotary drills, down the hole drills and hydraulic top hammer drills. In the study, the uniaxial compressive strength was included in the rotary drill model. Kahraman et al. (2000) defined a new drillability index from force-penetration curves of indentation tests and developed a mathematical penetration rate model for rotary drills using this new drillability index. Poderny (2000) presented the estimation of the main factors influencing on the rotary blast hole drilling. Kahraman (2002) statistically investigated the relationships between three different methods of brittleness and both drillability and bo-l ability using the raw data obtained from the expenmenial works of different researchers. He concluded that each method of measuring brittleness has its usage in rock excavation depending on practical utility, i.e. one method of measuring brittleness shows good correlation with the penetration rate of rotary drills, while the other method does not.

3 PERFORMANCE STUDIES

The drilling performance of rotary drills was measured on fourteen rock types in five open pit mines of Turkish Coal Enterprises. Drill type, bit type and diameter, hole length, feed pressure, rotation pressure, air pressure, net drilling time etc. were recorded in the performance forms (Table 1) during performance studies. Then, net penetration rates have been calculated from the measurements. The penetration rates for all observations are eiven in Table 2.

4 EXPERIMENTAL STUDIES

4.1. Uniaxial compressive strength test

Uniaxial compression tests were performed on trimmed core samples, which had a diameter of 33 mm and a length-to-diameter ratio of 2. The stress rate was applied within the limits of 0.5-1.0 MPa/s.

4.2. Brazilian tensile strength test

Brazilian tensile strength tests were conducted on core samples having a diameter of 33 mm and a height to diameter ratio of 1. The tensile load on the specimen was applied continuously at a constant stress rate such that failure will occur within 5 min of loading.

Table 1. The performance form of rotary drill in Kisrakdere marl (Soma)

Hole numbei	Rod number	Nel penetration ı.ıle (in/nun)	Average net penetration rale (in/mm)
1	1	0 82	0.66
		0 50	
2	1	0 74	0.64
	2	0 54	
1	1	0 78	0 64
	2	0 50	
4		0 74	0.54
	2	0.V3	
5	1	0.54	0.54
	2	0.54	
6	1	0 78	0.73
	2	0.67	
7	1	0 56	0 58
	2	0 60	
8	1	0 70	0.57
	2	0.43	
		Average'	0.61 ±0.07

Drill rig Reetlnll SK-S01. weight on hır 54 kN. rotational speed 120 rpm: air pressure' 4-^ har. bit 251 mm WC' Iricone-hit

Table 2. Net penetration rates for all observation

Ohsei tion numbei	va-Locution	Rock type	Net penetra-lion rale (in/nun)
1	• Soma/lsiklai	marl-1	0.83
2	Soma/IsiUai	nıaıi-2	0.74
3	Soma/lsıklaı	limestone	0.97
4	Soma/Kisiakdere	mai 1	0.61
5	Soma/Sankaya	mart	0 7
6	Tinaz/Bagyaka	limestone	1.47
7	Ot haneli	tuff	1.28
8	Ot haneli	marl	1 85
9	Oı haneli	sandy mall banded with tuff	1.98
10	Keleş	maiMimestone	1.52
11	Seyıtomeı	mail	2.73
12	Seyıtomeı	clayed mail	2.68
13	Tuncbılek/Pan.36	mail	1.67
14	Tmıcbılek/beke	mm 1	1.74

Bit 251 mm WC Incone-bit. thrust. 46-54 kN. rpm 118-120

4 ? *Point Load test*

The diametial point load test was earned out on the coies having a diametei ol 33 mm and a length of 66 mm and on the lectangular samples having a thickness ot 50 mm and a lenath ot 100 mm

4 4 *Schmidt hammei test*

N-type Schmidt hammei tests weie conducted in the field The Schmidt hammer was held on downwaid position and 10 impacts were earned out at each point and the peak iebound value was iecorded The lest was repeated at least thtee times on any lock type and a\erage value was lecoided as iebound number

4 5 *Cone nutentei test*

The cone mdentei developed by National Coal Boaid (NCB) (MRDE 1977) was used in this test The specimen sizes used in the test weie 12x12x6 mm

4 6 *Cachai liaidness test*

In this test a 8 mm-diametei bit having a cone angle ol 90 is pressed undei a load of 20 kg and the lock is drilled by 10 mm at 190 ipm The dulling time is defined as Cerchai haidness (Valantin 1974)

4 7 Impact \tient>th lest

The device designed by Evans & Pomeioy (1966) was used in the impact stiength test A 100 g sample of lock in the si/e lange 3 175 mm-9 525 mm is placed inside a cylindei of 42 86 mm diametei and a I 8 kg weight is diopped 20 times horn a height ot 30 48 cm on to the lock sample The amount of rock remaining in the initial size lange attei the test is teimed as the impact stiength index

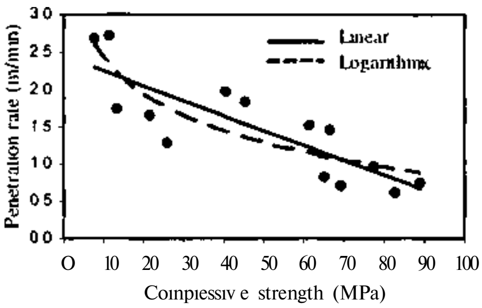
The aveiage iesults ot the all tests aie listed in Table 3

5 STATISTICAL ANALYSIS

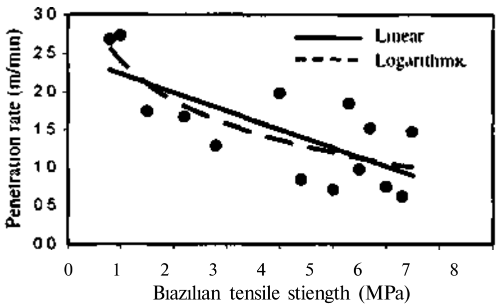
Penetiation uites weie con elated with the iock piopeities using the method ot least squaics regiession Both linear and logaiilhmic icgression analyses weie peitotmed The equation ot the best tit Une and the conelation cocihuent d) weie deteimmed toi each icgiession The plots ot penetration uite \eisus iock piopeities aie shown in Figuie 1 and all icgression equations arc given in Table 4 As seen in Figuie 1, the uniaxial compiessive stiength the point load sli ensrth

Table 3 The average results of the all tests

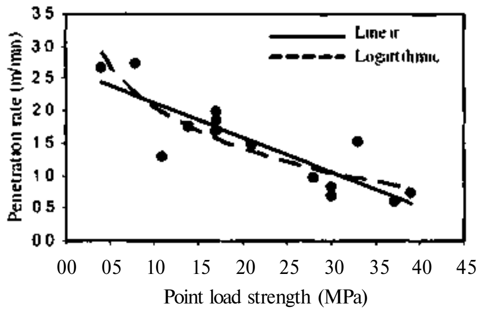
Location	Rock type	Uniaxial compressive strength (MPa)	Brazilian tensile strength (MPa)	Point load strength (MPa)	Schmidt hammer value	Cone indenter value	Cerchar hardness (sec)	Impact strength
Soma/Isiklar	marl 1	64 9±0 8	4 4±0 2	3 6±0 5	60±2 1	–	–	75 2±0 3
Soma/Isiklar	marl 2	88 7±1 0	6 0±0 4	3 9±0 7	57±2 1	2 9±0 4	30±9 0	85 0±1 0
Soma/Isiklar	limestone	77 5±2 9	5 5±0 2	2 8±1 0	62±1 4	3 4±0 2	19±4 0	65 0±2 5
Soma/Kısrakdere	marl	82 4±0 8	6 3±0 1	3 7±0 5	53±6 5	3 1±0 2	32±3 0	74 0±4 0
Soma/Sarikaya	marl	69 2±0 9	5 0±0 1	2 9±0 9	59±1 5	2 7±0 2	15±1 0	76 0±5 3
Tinaz/Bagyaka	limestone	66 6±1 1	6 5±0 3	2 1±0 3	54±1 4	3 5±0 3	11±1 0	71 0±1 5
Orhaneli	tuff	26 2±0 4	2 8±0 3	1 1±0 4	38±4 0	1 0±0 1	4±0 4	75 0±2 0
Orhaneli	marl	45 5±0 4	5 3±0 2	1 7±0 5	34±3 2	2 1±0 2	8±0 5	54 0±5 6
Orhaneli	sandy marl banded with tuff	40 4±2 1	4 0±0 2	1 7±0 5	34±8 7	1 6±0 1	8±1 1	55 0±1 5
Keles	marl limestone	61 5±1 5	5 7±0 3	3 3±0 3	34±3 5	1 9±0 4	11±0 5	–
Seyitomer	marl	11 4±0 5	1 0±0 1	0 6±0 2	42±4 0	–	–	67 5±0 5
Seyitomer	clayed marl	7 9±0 5	0 8±0 1	0 4±0 01	29±3 0	0 3±0 01	2±0 0	–
Tuncbilek/Panel 36	marl	21 4±1 2	2 2±0 1	1 7±0 1	53±1 5	–	–	69 9±0 8
Tuncbilek/beke	marl	13 5±1 0	1 5±0 1	1 4±0 3	52±3 6	–	–	70 4±0 8



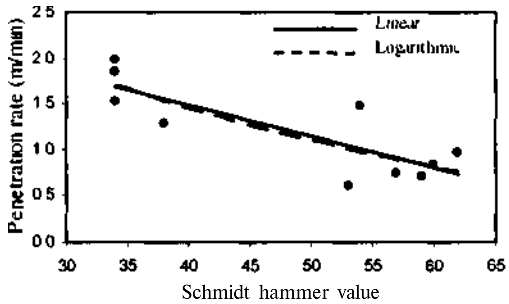
a) Penetration ıate vs uniaxial tonipiessive stiength



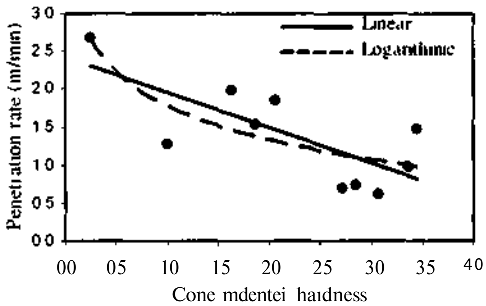
b) Penetration rate vs Bıanlıan tensile stiength



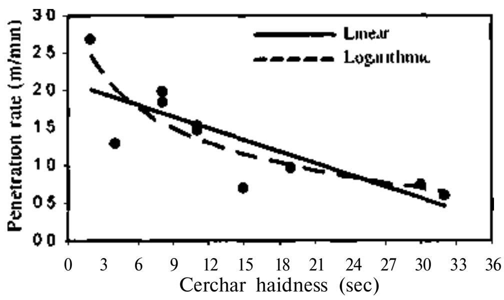
c) Penetıatıon ıate vs point load strength



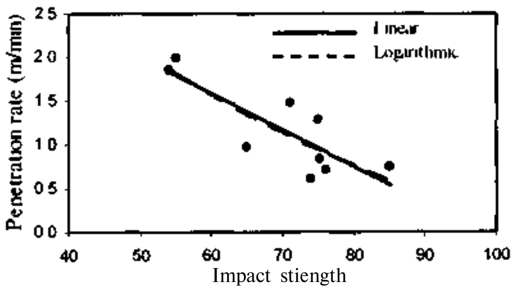
d) Penetration rate vs Schmidt hammer value



e) Penetıatıon rate vs cone ındenteı haıdness



t) Penetiation late vs Cerchar haidness



g) Penetration rate vs impact strength

Figure 1 The relations between penetration late and rock pıopertıes

Table 4. The regression equations and correlation coefficients*

Rock property	Regression equation: Linear		Logarithmic	
Uniaxial compr strength	$PR = -0.02\sigma_c + 2.47$	r = 0.84	$PR = -0.71 \ln \sigma_c + 4.07$	r = 0.84
Brazilian tensile strength	$PR = -0.24\sigma_t + 2.48$	r = 0.72	$PR = -0.75 \ln \sigma_t + 2.40$	r = 0.78
Point load strength	$PR = -0.53I_s + 2.64$	r = 0.85	$PR = -0.91 \ln I_s + 2.05$	r = 0.86
Schmidt hammer value	$PR = -0.034R_N + 2.85$	r = 0.82	$PR = -1.57 \ln R_N + 7.26$	r = 0.83
Cone indenter value	$PR = -0.47C_I + 2.42$	r = 0.74	$PR = -0.64 \ln C_I + 1.77$	r = 0.77
Cerchar hardness	$PR = -0.05CH + 2.10$	r = 0.80	$PR = -0.65 \ln CH + 2.92$	r = 0.85
Impact strength	$PR = -0.041IS + 4.04$	r = 0.82	$PR = -2.79 \ln IS + 12.98$	r = 0.84

**PR*- Penetration rate (m/min); *a,*• Uniaxial compressive strength (MPa): *IT,:* Brazilian tensile strength (MPa): /,: Point load index (MPa); Rv: Schmidt hammer value: *Cf.* Cone indenter value; *CH:* Cerchar hardness (sec); /5: Impact strength.

Schmidt hammer value, cerchar hardness and impact strength indicate strong correlations with the penetration rate. Omitting the soft rocks (compressive strength < 25 MPa) from the plots of penetration rate versus Schmidt hammer value and penetration rate versus impact strength was improved the correlations. The Brazilian tensile strength and, cone indenter hardness show fairly good correlations with the penetration rate.

6 CONCLUSIONS

Rotary blast hole drills are widely used in mining and civil engineering applications. An accurate prediction of penetration rate from rock properties and drill operational parameters is of vital importance for the efficient planning of projects. For the derivation of the penetration rate equations, rotary blast hole drills were observed in several rock types at different open pit mines and physical and mechanical properties of the rocks were determined in the field and in the laboratory. Then, the penetration rate of rotary blast hole drills was correlated with the rock properties and regression equations were developed.

The uniaxial compressive strength, the point load strength, Schmidt hammer value, cerchar hardness and impact strength exhibit strong correlations with the penetration rate. The equations derived from Schmidt hammer and impact strength values are valid for the rocks having uniaxial compressive strength over 25 MPa. The Brazilian tensile strength and cone indenter hardness show quiet good correlations with the penetration rate. From the test methods adopted in this study, the point load, the Schmidt hammer and the impact strength test are easier tests to carry out. In addition, they can be performed on unshaped samples and can be used easily in the field. So, these tests can be used for the rapid estimation of the penetration rate of rotary blast hole drills.

Further study is required to check the validity of the derived equations for the other rock types and for the different drilling conditions.

ACKNOWLEDMENTS

The authors wish to acknowledge to Turkish Coal Enterprises due lo providing facilities for site investigations. The participation in the congress has been supported by the Turkish Academy of Sciences, in the framework of the Young Scientist Award Program. (EA-TUBA-GEB1P/200I-I-I).

REFERENCES

Adamson. W. R. 1984. *Correlation of model excavating machine performance with rock properties ami rotary drilling performance data.* MSc. Thesis, Univ. of Queensland, 124 p.

Bilgin, N.. Eskikaya. S. & Dincer, T. 1993. The performance analysis of large diameter blast hole rotary drills in Turkish Coal Enterprises. In: Almgren. Kumar and Vagenas (Eds.). *The 2nd Int. Symp. on Mine Meclt. Automation, Lüleci:* 129-135.

Clark. G. B. 1979. *Principles of rock drilling.* Colorado School of Mines, 91 p.

Eskikaya, S. & Bilgin. N. 1993. *Research into ilrillabilitv and optimum drill hit usage for rotary drills in Turkish Coal Enterprises.* Final report, vol.2. Istanbul Technical University.

Evans, I. & Pomeroy. CD. 1966. *The strength, fracture and workability of coal.* Pergamon Press. London.

Fish, B. G. 1968. The basic variables in rotary drilling. *Mine & Quarry Engineering,* 27. 74-81.

Kahraman. S. 1997. *The development of a model lo obtain suitable drilling and blasting conditions in open pil mines and quarries.* PhD thesis (in Turkish). Istanbul Technical University. 328 p.

Kahraman. S. 1999. Rotary and percussive drilling prediction using regression analysis. *//;/. J. Rock Mech. Min. Sei.* 36: 981-989.

Kain aman. S. Balcı, C. Yazıcı, S & Bilgin. N. 2000. Prediction of the penetration late of rotary blast hole drills using a new drillability index. *Int. J. Rock Met It. Mm Sti.* 37: 729-43.

Kahiaman. S.. 2002. Correlation of TBM ami drilling machine performances with rock bııttleness. *En^. (îetıl.* 65: 269-283.

Kaıpuz. C . Pasamehmetoglu. A.C. Dincer. T. & Muftuoglu. Y. 1990 Diillabihty studies on the rotary blast hole drilling ot lignite overburden series. *Int. J. Surfine Min. Reel.* 4- 89-93

Miranda. A. & Mello-Mendes. F. I983. Disability and drilling methods. In: *Pun. Silt ISRM Congress.* Melbourne. 5: EI95-E200.

Morns. R. J. 1969. Rock drillability lelated to a roller cone bit. *Sin tet\ of Petroleum Engineer!,.* SPE 2389: 79-83.

MRDE. 1977 *NCB time inilenler.* MRDE Handbook No. 5. National Coal Board. London

Pandey. A. K.. Jam. A. K. & Singh. D. P. 1991. An investigation into rock drilling, *hit J Surfine Mm. Ret luintition* 5" 139-141

Poderny. R.Y. 2000. Basic factors estimation which define rotary blast hole drill production. In: *Plot: 9th Int. Svinp. tin Mine Pltuiii. imtl Equip. Seiet titin.* National Technical University of Athens: 673-678.

Reddish. D.J. & Yasar. E. 1996. A new portable rock strength index lest based on specific energy of drilling *Int. J. Ruck Meih. Min. Sei.* 33 (5): 543-548.

Rollow. A.G. 1962. Estimating drillability in the laboralory. In: *Prut. 5th Svmp. tin Ruck Metli..* Unıveısıty of Minnesota: 93-100.

Singh. D. P. 1969. Drillability and physical puiperties ot rocks. In: *Prut. Rink Merit. Sxmp..* University of Sydney: 29-34.

Villamın. A. 1974. Examen des différent procèdes classiques de détermination de la nocivité des roches vis-à-vis l'abattage mécanique. *Revue tie I'milustiie Minemle,* November: 134-140.

Warren. TM. 1981. Drilling model for soft-formation bits. *J. Petrol. Teihnol.* 33: 963-969.

Wijk. G. 1991. Rotary drilling prediction. *Int. J. Rock Mech. Min. S, i. & Getmiech. Ab.itr.* 28: 35-42.