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International Journal of Rock Mechanics and Mining Sciences 36 (1999) 981–989

International Journal of
Rock Mechanics
and Mining Sciences

www.elsevier.com/locate/ijrmms

Technical Note

Rotary and percussive drilling prediction using regression analysis

S. Kahraman*

University of Niğde, Faculty of Engineering and Arch., 51100 Niğde, Turkey

Accepted 16 June 1999

1. Introduction

The prediction of penetration rate is very important in mine planning. Total drilling costs could be estimated by using prediction equations. Also, one could use prediction equation to select the drilling rig type, which is best suited for given conditions. The drillability of rocks depends on many factors. Bit type and diameter, rotational speed, thrust, blow frequency and flushing are the controllable parameters. On the other hand the parameters such as rock properties and geological conditions are the uncontrollable parameters.

This paper has been prepared from a PhD thesis [1]. The thesis was aimed to develop a model for drilling and blasting in open pits and quarries.

2. Previous drillability studies

Drillability studies are mainly based on the empirical approach. There are different ways to define rock drillability. The concept of specific energy was proposed by Teale [2], Miller [3] and Pathinkar and Misra [4] as a guide to assess rock drillability. Rabia [5] stated that specific energy in terms of either unit volume or new surface area is not a fundamental intrinsic property of rock.

Many investigators have been tried to correlate drillability and various mechanical rock properties. Protodyakonov [6] described the coefficient of rock strength (CRS) test used as a measure of the resistance of rock by impact. The CRS test was then, modified by Paone et al. [7], Tandanand and Unger [8] and Rabia and Brook [9]. Tandanand and Unger [8] obtained simple relationships between the CRS and compressive strength. Rabia and Brook [9] used the modified test apparatus to determine the rock impact hardness number and developed an empirical equation for predicting drilling rates for both DTH and drifter drills. Singh [10] showed that compressive strength is not directly related to the drilling rate of a drag bit. Clark [11] stated that drilling strength is mainly dependent on hardness and triaxial strength of rock. Pathinkar and Misra [12] concluded that conventional rock properties such as compressive strength, tensile strength, specific energy, shore hardness, Mohs hardness do not individually give good correlation with penetration rate in percussive drilling. Miranda and Mello-Mendes [13] gave a rock drillability definition based on Vicker's microhardness. Howart and Rowland [14] correlated rock texture with rock strength and drillability. They concluded that the texture coefficient can be used as a predictive tool for the assessment of drillability and rock strength properties. Thuro and Spaun [15] have introduced a new rock property called 'destruction work' for toughness referring to drillability. To find this new rock property, a tough rock is loaded again several times, after the first loading under unconfined compression. Therefore, in the stress–strain diagram the vertices moved further to the right (in the post failure section). The area under the stress–strain envelope gives the destruction work. Researchers founded that there is a good correlation between destruction work and drillability.

Fish [16] developed a model for rotary drills with penetration rate directly proportional with thrust and inversely proportional with uniaxial compressive strength. Selim and Bruce [17] developed a penetration rate model for percussive drilling using stepwise linear regression analysis. The model is a function of the drill power and the physical properties of the rocks pene-

* Tel.: +90-388-225-0115; fax: +90-388-225-0112.
E-mail address: t.yalcinoz@ieee.org (S. Kahraman).

PII: S0148-9062(99)00050-9

trated. Also, penetration rate models of many workers [11,18–26] have appeared in the literature.

3. Drilling performance studies in the field

The drilling performance was measured on rotary, down the hole (DTH) and hydraulic top hammer drill rigs that drill blastholes in 27 formations at 16 different worksites including open pits, motorway sites and quarries (Table 1). Rotary drills were observed in 8 formations at 6 different sites. DTH drills were observed in 7 formations at 5 different sites. Hydraulic top hammer drills were observed in 14 formations at 5 different sites.

Drill type, bit type and diameter, hole length, feed pressure, rotation pressure, blow pressure, air pressure, net drilling time etc. were recorded in the performance forms (Table 2) during performance studies. Then, net penetration rates have been calculated and some information about the drills has been obtained from the production catalogues of the manufacturing firms.

4. Experimental studies

To determine the physical and mechanical properties of the rock drilled in situ, Schmidt hammer tests were carried out and block samples were collected as near as possible to the drilling sites. Then, standard test samples were prepared from these block samples and tests have been completed to measure compressive strength, tensile strength, impact strength, point load strength, seismic velocity, Young's modulus, density and quartz content. The summaries of the test results are given in Tables 3–5.

5. Statistical analysis

Because the drillability of rocks is affected by many factors, drillability cannot be analysed by using simple regression models. Therefore, the analysis must be carried out by using multiple regression methods. Multiple regression methods can be divided into two types as linear and nonlinear methods. In this study, the twin-logarithmic model, which is the one of the nonlinear methods was used. The equation representing the model can be written in the following form [27]:

$$Y = aX_1^{b_1}X_2^{b_2}, \ldots X_n^{b_n} \tag{1}$$

where, Y = Predicted value corresponding to the independent variable; a = Intercept; X_1, X_2,

Table 1
The sites at which performance studies were carried out

Site type	Location	Firm	Formation	Drill type	Date
Motorway site	Pozantı	Doğuş Constr. and Trade Co.	limestone, clayed limestone	hydraulic top hammer and rotary	24.4.1993–15.7.1993
Motorway site	Bahçe, Erikli	Tekfen Constr. and Institution Co.	dolomite, sandstone-1, limestone, marl, diabase, sandstone-2, altered sandstone, serpentine	hydraulic top hammer	27.7.1993–9.9.1993
Quarry	Adana, Misis	Adana Cement Co.	limestone, limestone	down the hole drill	11.7.1993–13.7.1993
Open pit	Yahyalı	Özkoyuncu Mining Co.	hematite, metasandstone	hydraulic top hammer	26.6.1995
Open pit	Konya	Crom-Magnesite Establishment	serpentine	hydraulic top hammer	21.8.1995
Open pit	Soma	TKİ-ELİ	marl	rotary	23.3.1996– 26.3.1996
Open pit	Seyitömer	TKİ-SLİ	marl	rotary	27.7.1996– 28.7.1996
Open pit	Tunçbilek	TKİ-GLİ	marl (36 pano), marl (Beke)	rotary	29.7.1996– 30.7.1996
Open pit	Emet	Etibank	metasandstone, limestone	rotary	31.7.1996
Open pit	Orhaneli	TKİ-BLİ	tuff	rotary	1.8.1996
Quarry	Tarsus	Özdemirler Mining Co.	dolomite	down the hole drill	16.8.1996
Quarry	Mersin	Ercan Mining Co.	limestone	down the hole drill	21.8.1996
Quarry	Ceyhan	Baykal Lime Co.	limestone, gravelled limestone	down the hole drill	29.8.1996
Quarry	Yumurtalık	Demircioğlu Mining Co.	limestone	down the hole drill	5.9.1996

Table 2
The performance form of DTH drill in limestone (Adana)[a]

Hole number	Rod number	Net penetration rate (m/min)	Average net penetration rate (m/min)	Total drilling time (min)
1	1	0.30	0.33	30
	2	0.33		
	3	0.37		
2	1	0.35	0.37	29
	2	0.39		
	3	0.37		
3	1	0.30	0.35	33
	2	0.37		
	3	0.37		
4	1	0.36	0.38	27
	2	0.40		
	3	0.39		
5	1	0.29	0.33	32
	2	0.33		
	3	0.39		
			Average: 0.35 ± 0.02	

[a] Date: July 11 1995; location: Adana; formation: limestone; drill type: DTH (Gemsa HPV 32); hammer type: Bulroc BR33; operational pressure: 7 bar; pulldown pressure: 10–15 bar; rotational pressure: 40 bar; air pressure: 7 bar; bit diameter: 89 mm; bit type: button bit; hole length: 10 m; hole inclination: 20°.

X_n = Independent variables; b_1, b_2, b_n = The regression coefficient of X_1, X_2, X_n.

Taking logarithms of both sides of the equation (1) converts the model into linear form as follows:

$$\log Y = \log a + b_1 \log X_1 + b_2 \log X_2 + \ldots + b_n \log X_n \quad (2)$$

The equation (2) can be written as the linear regression function:

$$Y = a + b_1 X_1 + b_2 X_2 + \ldots + b_n X_n \quad (3)$$

After carrying out the regression analysis, the models of penetration rate for rotary, DTH and hydraulic top hammer drills were developed. Variables used in the regression analysis are given respectively in Tables 3–5. The bit types used in rotary drills were tricone bits with tungsten carbide inserts. The bit types used in DTH and hydraulic top hammer drills were button bit. In the field study, the drills with new or very little worn bit were observed.

Regression analysis was carried out using a computing package called 'Statgraphics — Statistical Graphic System'. In Statgraphics, 'all possible regression' and 'stepwise regression' methods are used for the decision

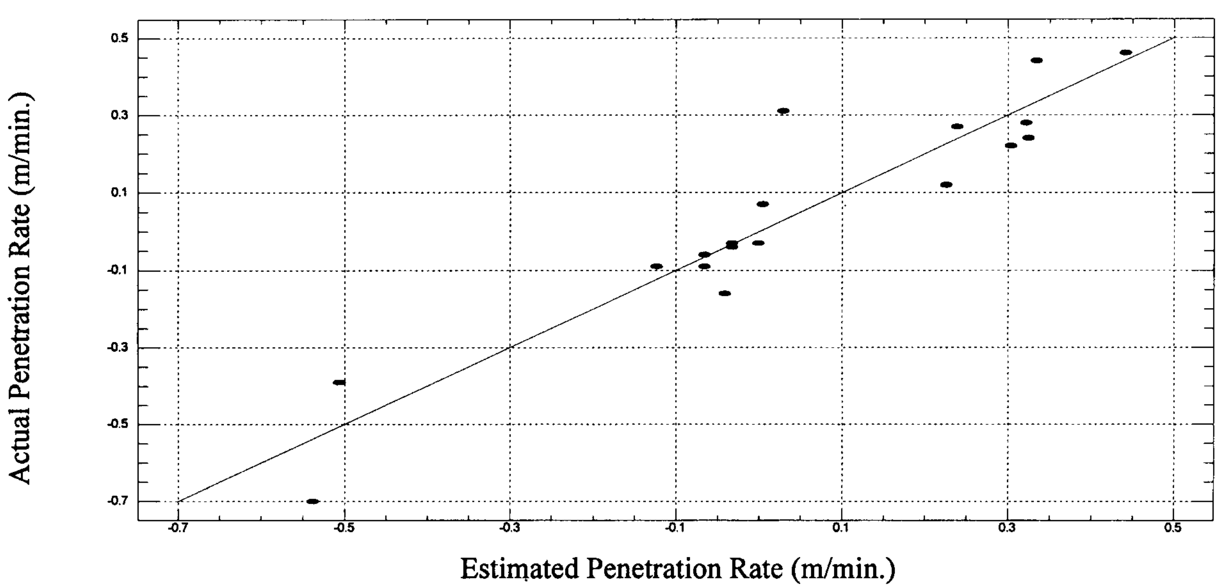

Fig. 1. Estimated penetration rate versus actual penetration rate for rotary drills.

Table 3
The variables used in the regression analysis of rotary drills

Location	Formation	Penetration rate (m/min)	Bit diameter (mm)	Weight on bit (kg)	Rotational speed (rpm)	UCS (MPa)	Tensile strength (MPa)	Rebound number	Impact strength	Point load strength (MPa)	P-wave velocity (km/s)	Elastic modulus (MPa)	Density (g/cm^3)	Quartz content (%)
Soma (Işıklar)	marl	0.94	251	5935	120	64.9	4.4	60	75.2	3.0	3.4	4758	2.45	0
Soma (Işıklar)	marl	0.69	251	5744	119	64.9	4.4	60	75.2	3.0	3.4	4758	2.45	0
Soma (Işıklar)	marl	0.81	251	4595	119	64.9	4.4	60	75.2	3.0	3.4	4758	2.45	0
Soma (Işıklar)	marl	0.91	251	5935	119	64.9	4.4	60	75.2	3.0	3.4	4758	2.45	0
Soma (Işıklar)	marl	0.81	251	5361	119	64.9	4.4	60	75.2	3.0	3.4	4758	2.45	0
Soma (Işıklar)	marl	0.87	251	5361	120	64.9	4.4	60	75.2	3.0	3.4	4758	2.45	0
Seyitömer	marl	2.86	251	6127	119	11.4	1.0	42	67.5	0.8	1.0	241	1.83	0
Seyitömer	marl	2.73	251	4595	119	11.4	1.0	42	67.5	0.8	1.0	241	1.83	0
Tunçbilek(36 pano)	marl	2.05	251	3063	120	21.4	2.2	53	69.9	1.7	1.9	1595	1.91	25
Tunçbilek(36 pano)	marl	1.67	228	5089	119	21.4	2.2	53	69.9	1.7	1.9	1595	1.91	25
Tunçbilek(Beke)	marl	1.74	251	4978	119	13.5	1.5	52	70.4	1.4	1.5	980	2.03	0
Tunçbilek(Beke)	marl	1.32	251	3829	119	13.5	1.5	52	70.4	1.4	1.5	980	2.03	0
Orhaneli	tuff	1.87	251	3180	119	10.1	0.9	35	69.3	1.2	1.2	193	1.85	35
Orhaneli	tuff	1.90	251	3829	122	10.1	0.9	35	69.3	1.2	1.2	193	1.85	35
Orhaneli	tuff	0.94	251	4595	72	10.1	0.9	35	69.3	1.2	1.2	193	1.85	35
Pozantı	clayed limestone	1.17	165	3981	75	45.1	6.0	68	80.5	4.6	3.3	2419	2.42	0
Emet	metasandstone	0.41	165	1493	72	70.5	5.5	38	75.8	6.3	3.7	13855	2.56	40
Emet	limestone	0.20	165	829	75	42.1	6.0	58	82.0	4.4	4.7	16757	2.70	0

Table 4
The variables used in the regression analysis of DTH drills

Location	Formation	Penetration rate (m/min)	Bit diameter (mm)	Piston diameter (mm)	Operat. Pressure (bar)	Pulldown pressure (bar)	Rotational pressure (bar)	Air pressure (bar)	UCS (MPa)	Tensile strength (MPa)	Rebound number	Impact strength	Point load strength (MPa)	P-wave velocity (km/s)	Elastic modulus (MPa)	Density (g/cm^3)
Adana	limestone	0.35	90	57	7	13	40	7	15.7	0.9	42	72.5	1.1	2.2	790	1.86
Misis	limestone	0.14	90	57	7	80	60	5	85.2	9.1	68	84.1	8	5.5	20,253	2.71
Tarsus	dolomite	0.28	90	57	7	15	50	7	96.3	10.7	55	80.6	9.8	5.6	19,000	2.98
Mersin	limestone	0.20	90	43	8	12	40	8	49.9	4.1	51	78.9	2.7	4.1	7903	2.66
Ceyhan	limestone	0.12	100	36	6	17	50	7	76.1	7.5	58	81.5	7.1	5.6	12,500	2.96
Ceyhan	gravelled limestone	0.23	100	36	7	22	45	6	36.2	2.7	47	75.9	2.5	3.3	2400	2.61
Yumurtalık	limestone	0.18	90	43	6	20	50	6	68.4	7.5	50	83.6	5.7	5	16,700	2.81

on which variables to include in the model. In this analysis, the first method was used. Hundreds of models for each drill type have been produced and each model has statistically been tested to find the best-fit model. The statistical results of the best models are summarised in Table 6. The best models developed for three drill types are given below.

For rotary drills:

$$PR = 1.05\frac{W^{0.824}RPM^{1.690}}{D^{2.321}\sigma_c^{0.610}} \quad R^2 = 0.87 \tag{4}$$

where, PR = estimated penetration rate (m/min); W = weight on bit (kg); RPM = rotational speed (rpm); D = bit diameter (cm); σ_c = uniaxial compressive strength (MPa).

For DTH drills:

$$PR = 3.24\frac{(Pd)^{0.826}}{R_n^{1.900}} \quad R^2 = 0.89 \tag{5}$$

where, PR = estimated penetration rate (m/min); P = operating pressure (bar); d = piston diameter (mm); R_n = Schmidt hammer (N-type) rebound number.

For hydraulic top hammer drills:

$$PR = 0.47\frac{b_{pm}^{0.375}}{\sigma_c^{0.534}q^{0.093}} \quad R^2 = 0.85 \tag{6}$$

where, PR = estimated penetration rate (m/min); b_{pm} = blow frequency (bpm); σ_c = uniaxial compressive strength (MPa); q = quartz content (%).

In addition to the statistical tests, to check the validation of the models, the estimated penetration rate versus the actual penetration rate is also plotted and is given in Figs. 1–3. It is shown in these figures that the points are distributed nearly uniformly about the diagonal line, suggesting that models are valid.

Multiple regression analysis showed that the most significant parameters affecting penetration rate for rotary drills are bit diameter, weight on bit, rotational speed and uniaxial compressive strength. The model for rotary drills is valid for the sedimentary formations, (especially lignite overburden series) and for air-operated rotary drills having tri-cone bit with tungsten carbide insert.

For DTH drills, Schmidt hammer rebound number and the product of operational pressure and piston diameter were included in the regression model. This model is valid for 90–100 mm bit diameter, 12–22 bar feed pressure, 40–60 bar rotational pressure and 5–8 bar air pressure.

For hydraulic top hammer drills, blow frequency, uniaxial compressive strength and quartz content were selected as the most significant parameters affecting penetration rate. The model for hydraulic top hammer

Table 5
The variables used in the regression analysis of hydraulic top hammer drills

Location	Formation	Penetration rate (m/min)	Bit diameter (mm)	Rock drill power (kW)	Blow frequ. (bpm)	Pulldown pressure (bar)	Blow pressure (bar)	Rotational pressure (bar)	UCS (MPa)	Tensile strength (MPa)	Rebound number	Impact strength	Point load strength (MPa)	P-wave velocity (km/sec.)	Elastic modulus (MPa)	Density (g/cm^3)	Quartz content (%)
Pozantı	limestone	0.68	76	14	2520	60	150	50	123.8	6.6	61	82.9	5.3	5.3	10,682	2.73	0
Pozantı	limestone	0.71	76	14	3000	60	110	60	123.8	6.6	61	82.9	5.3	5.3	10,682	2.73	0
Pozantı	limestone	0.82	76	14	3000	60	110	60	123.8	6.6	61	82.9	5.3	5.3	10,682	2.73	0
Bahçe	altered sandstone	1.70	76	15.5	3600	70	120	60	20.1	1.2	36	70.4	1.1	2	1566	2.55	17
Bahçe	altered sandstone	1.58	76	15.5	3600	70	120	60	20.1	1.2	36	70.4	1.1	2	1566	2.55	17
Bahçe	sandstone-2	0.65	76	15.5	3600	60	100	50	45.2	5.8	53	80.3	3.6	4.5	11,092	2.77	65
Bahçe	sandstone-1	0.40	76	15.5	3600	80	100	60	149.2	16.1	70	87.8	11.2	4.6	8746	3.00	80
Bahçe	dolomite	1.15	76	15.5	3600	70	120	60	68	6	59	83.4	3.5	6.3	6830	2.92	0
Bahçe	dolomite	1.10	76	15.5	3600	60	100	50	68	6	59	83.4	3.5	6.3	6830	2.92	0
Bahçe	dolomite	1.08	76	15.5	3600	80	130	60	68	6	59	83.4	3.5	6.3	6830	2.92	0
Erikli	limestone	1.21	76	15.5	3600	60	100	65	51.3	7	55	82.2	4.6	5.4	7193	2.74	0
Erikli	limestone	1.08	76	15.5	3600	60	100	60	51.3	7	55	82.2	4.6	5.4	7193	2.74	0
Erikli	limestone	1.19	76	15.5	3600	60	100	60	51.3	7	55	82.2	4.6	5.4	7193	2.74	0
Erikli	serpentine	0.95	76	11.5	2350	30	100	60	69.1	7.5	62	81.2	5.8	2.9	21,116	2.88	0
Erikli	serpentine	0.91	76	11.5	2350	30	100	60	69.1	7.5	62	81.2	5.8	2.9	21,116	2.88	0
Erikli	diabase	0.85	76	15.5	3600	100	120	70	110.9	10.1	64	89.5	10.3	5.2	10,901	2.96	0
Erikli	diabase	0.78	76	15.5	3600	100	120	170	110.9	10.1	64	89.5	10.3	5.2	10,901	2.96	0
Erikli	marl	1.41	76	17.5	3600	75	100	65	39.5	5.2	56	76.1	2.7	3.1	4060	2.20	0
Pozantı	clayed limestone	0.97	89	11.5	2350	10	100	10	45.1	6	68	80.5	4.6	3.3	2419	2.42	0
Pozantı	clayed limestone	1.10	89	14	2520	60	150	50	45.1	6	68	80.5	4.6	3.3	2419	2.42	0
Pozantı	clayed limestone	1.17	89	14	2520	60	150	50	45.1	6	68	80.5	4.6	3.3	2419	2.42	0
Erikli	marl	1.27	89	17.5	3200	75	100	65	39.5	5.2	56	76.1	2.7	3.1	4060	2.20	0
Yahyalı	metasandstone	1.42	89	15.5	3200	60	90	60	25.7	5.8	54	85	4.2	5.2	10,562	2.70	57
Konya	serpentine	1.12	89	17.5	3200	100	110	75	54.3	11.7	59	90.3	13.2	5	20,224	2.63	30
Pozantı	limestone	0.73	102	14	2520	60	150	50	123.8	6.6	61	82.9	5.3	5.3	10,682	2.73	0
Pozantı	clayed limestone	1.20	102	14	2520	60	150	50	45.1	6	68	80.5	4.6	3.3	2419	2.42	0
Pozantı	clayed limestone	1.15	102	14	2520	60	150	50	45.1	6	68	80.5	4.6	3.3	2419	2.42	0
Yahyalı	hematite	0.75	102	25	2040	110	100	110	61.8	6.6	44	84.3	6.7	2.8	19,566	3.61	0

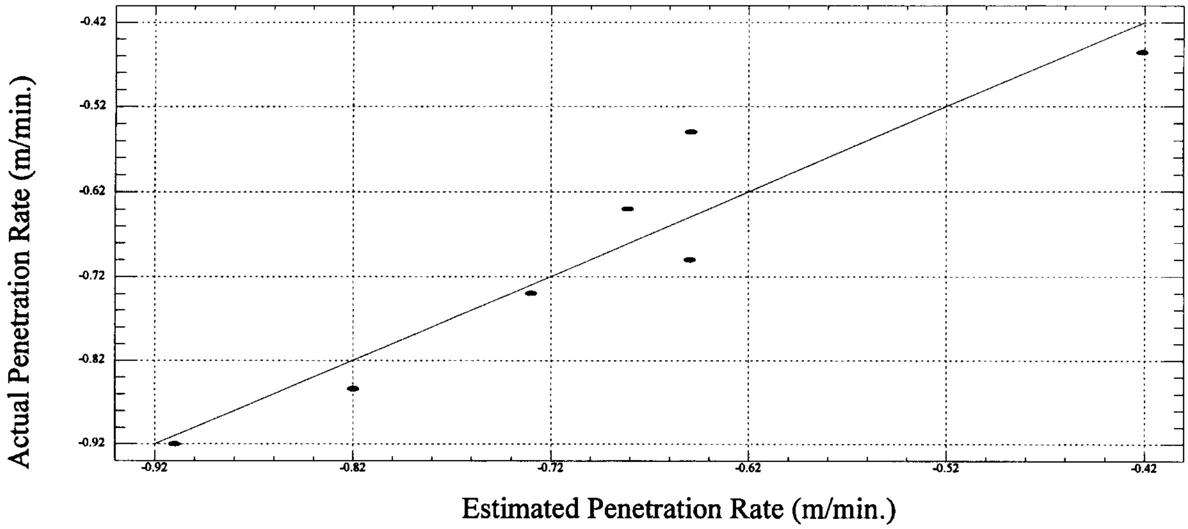

Fig. 2. Estimated penetration rate versus actual penetration rate for DTH drills.

is valid for 76–102 mm bit diameter, 11.5–17.5 kW rock drill impact power, 60–100 bar feed pressure, 100–150 bar blow pressure and 50–70 bar rotational pressure.

The last two models are also valid for sedimentary formations like limestones.

6. Conclusions

As a result of the research carried out, 27 formations in 16 different worksites including open pit mines, motorway sites and quarries, penetration rate models for rotary, DTH and hydraulic top hammer drills have been developed. To check the validation of the models, each model has statistically been tested. In the study, for rotary drills uniaxial compressive strength, for DTH drills Schmidt hammer rebound number and for hydraulic top hammer drills uniaxial compressive strength and quartz content have been determined as the dominant rock property.

Acknowledgements

The author would like to thank Professor Nuh Bilgin for his many helpful comments and suggestions during the author's PhD study.

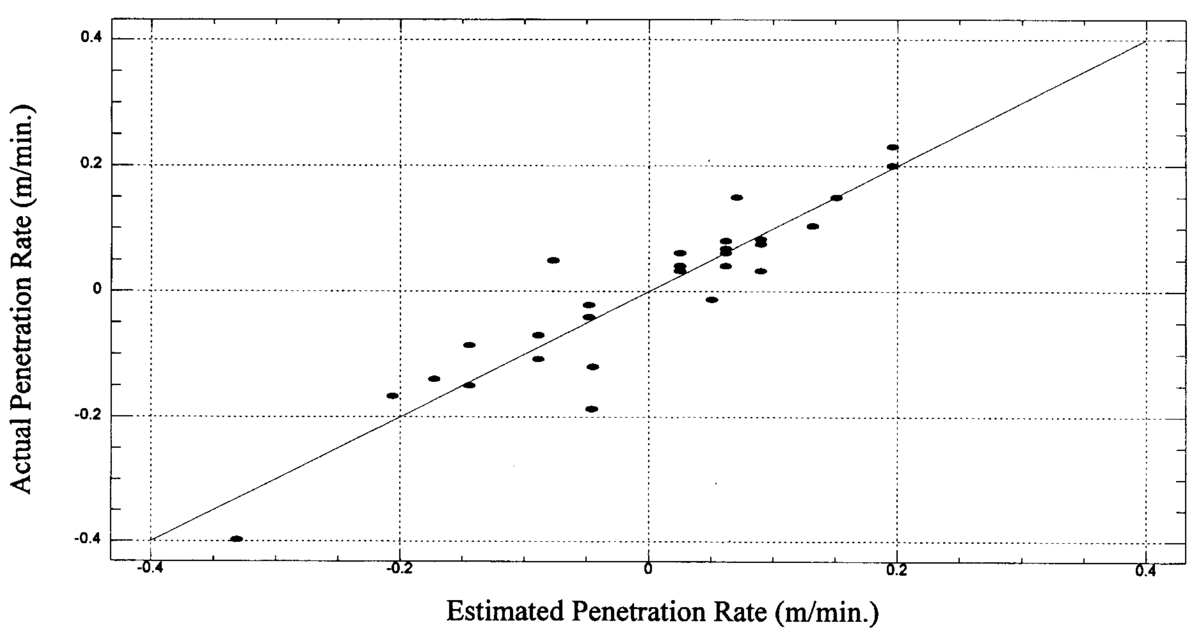

Fig. 3. Estimated penetration rate versus actual penetration rate for top hammer drills.

Table 6
The statistical results of the models developed

Drill type	Equation no	Independent variables	Coefficient	Confidence interval		Standard error	Model error	Significance level	Confidence level	Determination coeff. (R^2)	Adjusted determination coefficient	t Value	Tabulated t	F value	Tabulated F
				lower limit	upper limit										
Rotary drill	(4)	constant	0.021	−2.742	2.785	1.279		0.987				0.016			
		bit diameter	−2.321	−4.304	−0.338	0.918		0.025				−2.529			
		weight on bit	0.824	0.397	1.252	0.198	0.117	0.001	95%	0.87	0.83	4.167	± 1.761	22.72	3.34
		RPM	1.690	0.506	2.873	0.547		0.009				3.086			
		UCS	−0.610	−0.807	−0.414	0.091		0.000				−6.728			
Down the hole drill	(5)	constant	0.511	−1.883	2.905	0.862		0.585				0.593			
		oper. pressure X					0.064		95%	0.89	0.84		± 2.010	17.17	6.61
		piston diameter	0.826	0.183	1.468	0.231		0.023				3.569			
		rebound number	−1.900	−2.989	−0.811	0.392		0.008				−4.847			
Hydraulic top hammer	(6)	constant	−0.325	−1.326	0.675	0.485		0.508				−0.671			
		blow frequency	0.375	0.091	0.658	0.137		0.012				2.732			
		UCS	−0.534	−0.631	−0.437	0.047	0.055	0.000	95%	0.85	0.83	−11.399	± 1.708	46.96	3.39
		quartz content	−0.093	−0.130	−0.056	0.018		0.000				−5.243			

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