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Predictive Models for Roadheaders' Cutting Performance in Coal Measure Rocks

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ABSTRACT

Roadheaders offer a unique capability and flexibility for the excavation of soft to medium strength rock formations, hence; are extensively used in underground mining and tunneling operations. A critical issue in successful roadheader application is the ability to evaluate and predict the machine performance. The main objective of this research study is to investigate the cutting performance of roadheaders in coal measure rocks by paying special attention to the influence of discontinuity orientation (alpha angle) and the specific energy. With this respect, a database was established from detailed field data including the measured instantaneous cutting rates (ICR) and geomechanical parameters of the coal measure rocks for each cutting condition in the tunnels. The database was then analyzed by utilizing the statistical method in order to yield new predictive models. The influence of alpha angle (the angle between tunnel axis and the planes of weakness) on roadheader performance was investigated and the correlation between them was found to be good (R^2=0.96). The analysis of the specific energy also showed that there is a relatively good relation (R^2=0.91) between this parameter and ICR. Finally, the new predictive models for ICR (with respect to alpha angle and specific energy) showed to have highly correlated relationships within the limits of measured values and hence may successfully be used to evaluate the performance of medium-duty roadheaders in coal measure rocks.

Keywords: Performance prediction, Roadheader, Alpha angle, Specific energy, Coal measure rocks

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INTRODUCTION

The more widespread use of mechanical excavators, such as roadheaders, continuous miners, impact hammers and tunnel boring machines is a trend set by increasing pressure on the mining and civil construction industries to move away from the conventional drill and blast methods to increase productivity, decrease production costs, improve competitiveness and safety, and reduced number of personnel. Roadheaders are a unique class of mechanical excavation machines used in the mining industry particularly in coal mining and industrial minerals. Roadheaders are very versatile excavation machines favored in mining operation due to a high degree of mobility, flexible cutting profile (i.e., horseshoe), selective mining, providing immediate access to the face and the capability to cut medium strengths rocks with compressive strength of up to about 100 MPa (Copur et al, 1998).

Performance prediction is an important issue for successful roadheader application and generally deals with machine selection, production rate and bit consumption. Performance prediction encompasses the assessment of instantaneous cutting rate (ICR), bit consumption rates and machine utilization for different geological units. The instantaneous cutting rate is the production rate during cutting time (tons or m³ /cutting hour). Bit or pick consumption rate refers to the number of picks changed per unit volume or weight of rock excavated (picks / m³ or m³ / pick). Machine utilization is the percentage of time used for excavation during the project. The roadheader production rate and pick consumption are controlled by several parameters including (Rostami et al, 1994):

- Rock parameters, such as rock compressive and tensile strength, etc.
- Ground conditions, such as degree of jointing (RQD), joint conditions, ground water, etc.
- Machine specification, including machine weight, cutter head power, sumping, arcing, lifting, and lowering forces, cutter head type (axial or transverse), bit type, size, number and allocation of bits on the cutter head, the capacity of back up system, and other characteristics.
- Operational parameters, such as shape, size, and length of opening, inclination, quality of labor, etc.

A combination of these parameters determines the production rate of a given machine in a certain ground condition.

The paper, first gives a brief background of roadheader performance prediction models and then information about a database from the detailed field data including machine performance and geotechnical parameters in entries from the Tabas Coal Mine project (the largest and fully mechanized coal mine in Iran). Thereafter, the paper highlights some of the previous attempts made to construct models to predict the roadheaders performance in Tabas coal mine. Using the data, subsequently, a set of performance prediction equations are developed.

BACKGROUND ON PERFORMANCE PREDICTION MODELS FOR ROADHEADERS

Sandbak (1985) and Douglas (1985) used a rock classification system to explain changes in roadheader's advance rates at San Manuel Copper Mine in an inclined drift at an 11% grade (Bilgin et al., 2004). Gehring (1989) studied the relationship between ICR and rock uniaxial compressive strength (UCS) for a milling type roadheader with 230kW cutter head power and an Alpine Miner AM 100 ripping type roadheader with 250kW cutter head power. He developed following equations without giving correlation coefficients:

$$ICR = \frac{719}{UCS^{0.78}} \tag{1}$$

for ripping type roadheaders, and

$$ICR = \frac{1739}{UCS^{1.13}} \tag{2}$$

for milling type roadheaders

Where ICR denotes as cutting performance (m³/hr), and UCS as the uniaxial compressive strength (MPa). Based on rock compressive strength and rock quality designation, Bilgin et al. (1988, 1990, 1996, 1997, 2004) had also developed a performance (ICR) equation as:

$$ICR = 0.28 \cdot P \cdot \left(0.974\right)^{RMCI} \tag{3}$$

$$RMCI = UCS \times \left(RQD/100\right)^{2/3} \tag{4}$$

where P is the power of cutting head (hp), RMCI is the rock mass cuttability index and RQD is the rock quality designation (%). Copur et al. (1997, 1998) studied the variation of cutting rate with UCS based on available field performance data for different types of roadheaders at different geological conditions. They stated that if power and weight of roadheaders were considered together, in addition to rock compressive strength, the cutting rate predictions would be more realistic. The predictive equations for transverse (ripping type) roadheaders are as follows:

$$ICR = 27.511e^{0.0023(RPI)} \tag{5}$$

$$RPI = P \times W / UCS \tag{6}$$

Here, RPI, UCS, W, P and e denote roadheader penetration index, uniaxial compressive strength (MPa), roadheader weight (t), power of cutting head (kW), and base of natural logarithm, respectively. Thuro and Plinninger (1999) determined the relationship between the cutting rate and the uniaxial compressive strength for 132kW roadheader. They found that the correlation between UCS and cutting performance is not sufficient in predicting the cutting rate. They obtained higher correlation by putting the cutting performance against specific destruction work (kJ/m³). Specific destruction work $\left(W_z\right)$ is defined as the measurement for the quantity of energy required for destruction of a rock sample or – in other words – the work, necessary to built new surfaces (or cracks) in rock. They presented the following predictive equation:

$$ICR = 107.6 - 19.5\ln\left(W_z\right) \tag{7}$$

where W_z is the cutting performance (m³/hr) and the specific destruction work (kJ/m³).

Another way of predicting the machine instantaneous cutting rate is to use specific energy described as the energy spent to excavate a unit volume of rock material. Widely accepted rock classifications and assessments for the performance estimation of roadheaders are based on the specific energy found from core cutting tests. Detailed laboratory and in situ investigations by McFeat-Smith and Fowell (1977, 1979) showed that there was a close relationship between specific energy values obtained separately from both core cutting tests and cutting rates for medium and heavy weight roadheaders.

One of the most accepted methods to predict the cutting rate of any excavating machine is to use, cutting power, specific energy obtained from full scale cutting tests and energy transfer ratio from the cutting head to the rock formation as indicated in the following equation (Rostami et al, 1994):

$$ICR = k\frac{P}{SE_{opt}} \tag{8}$$

where P is the cutting power of the mechanical miner (kW), SE_{opt} is the optimum specific energy (kWh/m³), and k is the energy transfer coefficient depending on the mechanical miner utilized. Rostami et al. (1994) strongly emphasized that the predicted value of the cutting rate was more realistic if the specific energy value in the equation was obtained from the full-scale linear cutting tests in optimum conditions using real life cutters. Rostami et al. (1994) pointed out that k changed between 0.45 and 0.55 for roadheaders and from 0.85 to 0.90 for TBMs.

DESCRIPTION OF TABAS COAL MINE PROJECT

Tabas coal mine, the largest and unique fully mechanized coal mine in Iran, located in central part of Iran near the city of Tabas in Yazd province and situated 75 km far from southern Tabas. The mine area is a part of Tabas-Kerman coal field. The coal field is divided into 3 parts in which Parvadeh region with the extent of 1200 Km^2 and 1.1 billion tones of estimated coal reserve is the biggest and main part to continue excavation and fulfillment for future years.

The Coal seam has eastern-western expansion with reducing trend in thickness toward east. Its thickness ranges from 0.5 to 2.2 m but in the majority of conditions it has a consistent 1.8 m thickness. Room and pillar and long wall mining methods are considered as the main excavation methods in the mine. The use of roadheaders in Tabas coal mine project was a consequence of mechanisation of the work. Coal mining by the long-wall method with powered roof supports requires rapid advance of the access roads. On the other hand, the two alternatives for mining very thick coal seams, i.e. room-and-pillar and long wall in flat seams, also requires the use of roadheader driving galleries in the coal seams. Four DOSCO MD 1100 roadheaders of 34 t in weight, with a 82-kW axial cutting head mainly used in driving galleries with coal measure rocks (coal, siltstone and mudstone) in the Tabas coal mine. Figs.1 and 2 show DOSCO MD 1100 roadheader and typical view of rock formations encountered in the tunnels' route. Table 1 indicates the basic specifications of these roadheaders (Dosco Ltd, 2008).

Figure 1. DOSCO MD1100 roadheader fitted with axial boom used in Tabas Coal Mine project (Dosco Ltd, 2008).

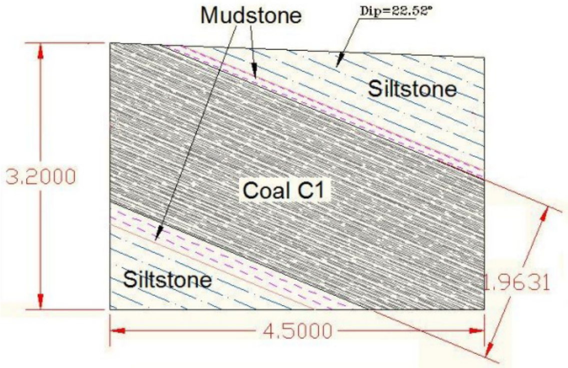

Figure 2. Typical view of rock formations encountered in the tunnels route. (All dimensions are in meter).

As seen in Table 2, a comprehensive database of field performance from Tabas Coal Mine was established by using the detailed data including machine performance and geomechanical parameters for 62 cutting cases in tunnels and entries of the proposed project (Ebrahimabadi, 2010).

PREVIOUS PREDICTIVE MODELS IN TABAS COAL MINE

Studies regarding the performance prediction of roadheaders in the Tabas coal mine project were done from a detailed field data including

Table 1. Typical specifications of DOSCO MD 1100 roadheaders (Dosco Ltd, 2008)

Machine weight (Base machine)	34 tons
Total power (Standard machine)	From 157 kW
Power on cutting boom (Standard machine)	82 kW axial, 112 kW transverse
Hydraulic system working pressure	140 bar
Tracking speeds – Sumping/Flitting	0.038/0.12 m/sec
Ground pressure	1.4 kg/cm²
Machine length	8060 mm
Machine width	3000 mm
Machine height	1700 mm

machine performance and geomechanical parameters in tunnels and entries of the project. Consequently, a comprehensive field performance database was established (Ebrahimabadi, 2010; Ebrahimabadi et al., 2011). As a result, models to predict the performance of roadheaders based on brittleness index were developed. Rock mass brittleness index (RMBI) is defined in order to investigate the influence of intact and rock mass characteristics on roadheaders performance. Results demonstrated that RMBI is highly correlated to instantaneous cutting rate (ICR) (R^2=0.98). Moreover, through the further analysis and normalization, pick consumption index (PCI) was introduced as a parameter having a good relation with pick or bit consumption rates (PCR) (R^2=0.94). The predictive equations were as follows (Ebrahimabadi, 2010; Ebrahimabadi et al., 2011):

$$RMBI = e^{\left(\frac{UCS}{BTS}\right)} \times \left(\frac{RQD}{100}\right)^3 \qquad (9)$$

$$ICR = 30.74 RMBI^{0.23} \qquad (10)$$

$$PCI = e^{RMBI} \times \left(\frac{UCS}{P}\right) \qquad (11)$$

$$PCR = 45.10 PCI^{-0.15} \qquad (12)$$

where RMBI is the rock mass brittleness index, UCS is the uniaxial compressive strength of rock (MPa), BTS is the Brazilian tensile strength of rock (MPa), RQD is the rock quality designation of the rock mass (%), PCI is the pick consumption index, PCR is the pick consumption rate (m³/pick), and P is the cutter head power (kW). In the Equation 11, P is considered to be 82 kW (the cutter head power of the DOSCO MD 1100 roadheader).

It should be noted that the Equations 9-12 were achieved from the analysis of 42 cutting cases. After gathering additional data from other cutting cases and subsequently establishing a database with 62 cutting cases, Equation 10 has been modified to the following equation:

$$ICR = 9.07 \ln\left(RMBI\right) + 29.93 \qquad (13)$$

It must be stated that in the above predictive equations don't include the influence of discontinuities orientation and the specific energy. Therefore, in this research study new models are developed in order to involve these factors.

DATABASE ESTABLISHMENT

The type and density of discontinuities have a crucial importance on both the behavior of a rock mass and machine advancement. In order

Table 2. Summary of rock properties, roadheaders performance, rock mass brittleness index, alpha angle and the specific energy for all cutting cases (Ebrahimabadi, 2010)

Case No.	Representative uniaxial compressive strength (MPa)	Representative Brazilian tensile strength (MPa)	RQD (%)	Measured instantaneous cutting rate (m^3/hr)	Calculated rock mass brittleness index (RMBI)	Calculated alpha angle (Deg.)	Calculated specific energy (MJ/m^3)
1	14.8	3.8	19	22.2	0.36	46	4.53
2	15.2	3.9	19	25.3	0.36	52	4.60
3	15.2	3.8	20	24.8	0.41	52	4.61
4	15.4	4.0	19	23.7	0.35	46	4.65
5	15.3	3.9	19	23.2	0.38	46	4.62
6	15.0	3.9	19	22.8	0.30	46	4.57
7	15.6	3.9	20	27.1	0.40	50	4.68
8	14.5	3.7	20	25.7	0.39	48	4.46
9	16.2	4.2	18	25.6	0.28	52	4.79
10	15.4	4.0	18	20.2	0.28	45	4.63
11	16.9	4.2	20	28.2	0.46	50	4.91
12	14.3	3.8	19	24.4	0.30	47	4.44
13	15.5	4.0	19	26.4	0.36	50	4.67
14	17.2	4.1	20	25.7	0.54	47	4.96
15	23.9	4.7	27	41.5	3.04	52	6.03
16	27.2	5.3	28	46.2	3.89	54	6.48
17	20.1	4.5	23	32.2	1.02	53	5.45
18	14.1	3.6	19	16.7	0.34	40	4.38
19	15.0	3.8	20	17.4	0.39	43	4.57
20	14.4	3.8	19	16.8	0.31	41	4.45
21	14.8	3.9	18	17.0	0.28	42	4.53
22	14.7	3.8	19	17.5	0.30	43	4.51
23	15.7	4.0	19	16.8	0.37	41	4.69
24	16.4	4.3	18	16.7	0.27	40	4.82
25	15.1	3.9	19	16.1	0.35	41	4.58
26	14.5	3.7	19	17.7	0.34	42	4.47

Case No.	Representative uniaxial compressive strength (MPa)	Representative Brazilian tensile strength (MPa)	RQD (%)	Measured instantaneous cutting rate (m^3/hr)	Calculated rock mass brittleness index (RMBI)	Calculated alpha angle (Deg.)	Calculated specific energy (MJ/m^3)
27	15.1	3.9	19	16.0	0.33	40	4.58
28	15.2	4.0	19	17.0	0.31	41	4.60
29	14.4	3.7	19	14.6	0.33	39	4.46
30	15.6	3.9	20	19.0	0.41	45	4.68
31	14.5	3.7	18	17.7	0.29	42	4.46
32	14.7	3.8	19	15.7	0.34	40	4.50
33	17.0	4.2	20	18.7	0.48	44	4.92
34	15.7	4.0	19	16.8	0.36	40	4.70
35	16.0	3.9	20	18.3	0.49	44	4.74
36	16.2	3.8	21	26.4	0.70	49	4.78
37	16.7	3.9	22	25.3	0.78	51	4.88
38	17.2	3.9	22	28.5	0.85	50	4.97
39	17.3	4.2	21	25.4	0.58	53	4.98
40	19.2	4.5	24	29.4	0.95	51	5.31
41	15.0	3.9	19	22.4	0.30	46	4.56
42	21.0	3.8	20	36.4	2.08	52	5.59
43	22.3	3.9	20	37.7	2.44	52	5.79
44	25.6	4.2	19	40.4	3.26	53	6.26
45	26.7	4.3	19	41.1	3.52	52	6.42
46	26.7	4.3	19	41.1	3.52	52	6.42
47	27.2	4.3	19	41.4	3.63	52	6.49
48	27.6	4.4	19	41.6	3.73	52	6.55
49	28.0	4.4	19	41.8	3.80	53	6.59
50	19.2	3.7	21	34.0	1.55	53	5.30
51	25.1	4.1	19	40.0	3.14	49	6.19
52	27.0	4.3	19	41.3	3.59	50	6.46
53	27.1	4.3	19	41.3	3.61	46	6.47

Case No.	Representative uniaxial compressive strength (MPa)	Representative Brazilian tensile strength (MPa)	RQD (%)	Measured instantaneous cutting rate (m³/hr)	Calculated rock mass brittleness index (RMBI)	Calculated alpha angle (Deg.)	Calculated specific energy (MJ/m³)
54	27.4	4.3	19	41.5	3.67	39	6.51
55	27.5	4.3	19	41.5	3.69	41	6.53
56	27.6	4.3	19	41.6	3.72	45	6.54
57	27.7	4.4	19	41.7	3.75	53	6.56
58	27.9	4.4	19	41.8	3.78	52	6.58
59	28.0	4.4	19	41.8	3.80	44	6.59
60	28.1	4.4	19	41.9	3.83	42	6.61
61	27.9	4.4	19	41.8	3.79	53	6.59
62	28.2	4.4	19	41.9	3.85	53	6.62

to be able to quantify the influence of discontinuity orientation on roadheader performance, the alpha angle that is the angle between the tunnel axis and the planes of weakness are used. In order to calculate the alpha angle, the orientation of the discontinuities and the driven direction of the roadheaders were measured in the field. The alpha (α) in degrees can be calculated using the following equation (Yagiz, 2008):

$$\alpha = \arcsin\left(\sin \alpha_f . \sin\left(\alpha_t - \alpha_s\right)\right) \tag{14}$$

where α_f and α_s are the dip and strike of the encountered planes of weakness in the rock mass, respectively. α_t is direction of the tunnel axis. Moreover, specific energy is one of the most important factors in determining the efficiency of cutting systems. Widely accepted rock classification and assessment for the performance estimation of roadheaders was based on the specific energy found from core cutting tests. The test involved instrumented cutting tests on 76mm diameter cores at a depth of cut of 5mm, cutting speed of 150 mm/s with a chisel-shaped tungsten carbide tool having 10% cobalt by weigh, 3.5-µM nominal grain size, rake angle of (-5°), back clearance angle of 5° and tool width of 12.7 mm (Fowell and McFeat-Smith, 1979). Detailed laboratory and in situ investigations carried out by Fowell and McFeat-Smith (1979) showed that there was a close relationship between specific energy values obtained from core cutting tests and cutting rates of medium and heavy-weight roadheaders. They formulated core cutting specific energy as in Equation 15 (Hartman, 1992):

$$\begin{aligned} SE = & -4.38 + 0.14\left(0.0377UCS + 0.254\right)^2 \\ & + 3.30UCS^{1/3} + 0.000018\left(0.441UCS - 8.37\right)^3 + 0.0057CC \end{aligned} \tag{15}$$

Where SE is the specific energy (MJ/m³), UCS is the rock uniaxial compressive strength (MPa) and CC is the cementation coefficient. The cementation coefficient is based on petrographic descriptions of the rock. In order to quantify the degree and type of cementation, McFeat-Smith (1977) carried out a study on thin sections and photomicrographs of broken surfaces of a range of sedimentary rock types. The following conclusions were reached:

1. The type of cementation should be assessed according to the hardness of the cementing material.

2. The grain size of quartz cements ie sand, silt and clay influence the strength of the bond and should be represented in that order.
3. The degree of cementation is significant in extreme cases and major variations in the porosity of a rock provide a suitable measure of this.

The quantification of a Cementation Coefficient (CC) which has been constructed according to these observations is as follows:

CC=1 for non cemented rocks or those having greater than 20 per cent voids, CC=2 for Ferruginous cement, CC=3 for Ferruginous and Clay cement, CC=4 for Clay cement, CC=5 for Clay and Calcite cement, CC=6 for Calcite or Halite cement, CC=7 for Silt, Clay or Calcite with Quartz overgrowths, CC=8 for Silt with Quartz overgrowths, CC=9 for Quartz cement, Quartz mosaic cement and CC=10 for Quartz cement with less than 2 per cent voids. According to this quantification and based on field observations, CC=5 is considered for the coal measure rocks in the Tabas coal mine.

Detailed field investigations were carried out where the machine performance and the geomechanical properties of the coal measure rocks encountered in the Tabas coal mine project were collected. With this regard, the values of instantaneous cutting rate were measured in the field and the values of rock mass brittleness index, alpha angle and the specific energy were calculated using Equations 9, 14 and 15, respectively for each cutting case, as listed in Table 2.

NEW PREDICTIVE MODELS BASED ON ALPHA ANGLE AND SPECIFIC ENERGY

After the establishment of the database, statistical analysis was used to investigate the relation between the parameters. Subsequently, the relation between ICR, RMBI and α angle was investigated and the correlation between them was found to be good (R^2=0.96). Consequently, the following predictive equation for calculating the ICR with respect to α was obtained:

$$ICR = 5.56RMBI + 0.60\alpha - 8.17 \quad (16)$$

Where RMBI is the rock mass brittleness index, and α is the angle between tunnel axis and the planes of weakness in degrees. Summary of statistical model is given in Table 3.

Comparison between the measured and the predicted ICR is given in Figure 3 for each cutting case. Using Equation 16 for prediction of ICR with respect to α, a reliable relationship between the predicted and the measured ICR was obtained with R^2 = 0.96. Table 4 shows the values of measured and predicted ICR with percentage of relative errors between them.

In this study, the specific energy was calculated for each cutting case and its relation with the instantaneous cutting rate was then investigated. Consequently, the relation between them was found to be relatively good (R^2=0.91), as demonstrated in Figure 4. Summary of statistical model is given in Table 5. The predictive equation is as follows:

$$ICR = -0.18SE^3 + 28.57SE - 92.82 \quad (17)$$

where SE is specific energy (MJ/m^3). Using Equation 17 for the prediction of ICR with respect to the specific energy, another relationship between the predicted and the measured ICR was obtained with R^2 = 0.91 (Figure 5). Table 4 shows the values of measured and predicted ICR with percentage of relative errors between them.

Table 3. Summary of statistical model

Model Type	R [a]	R^2	Adjusted R^2	Std. error of the estimation
linear	0.98	0.96	0.96	2.2227

Dependent variable: Measured ICR (m³/hr)

a. Predictors: (Constant), RMBI, α

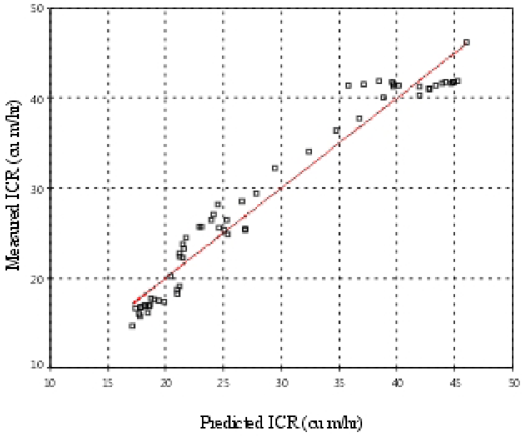

Figure 3. Linear regression between measured ICR and predicted ICR (with respect to alpha angle) (R^2=0.96).

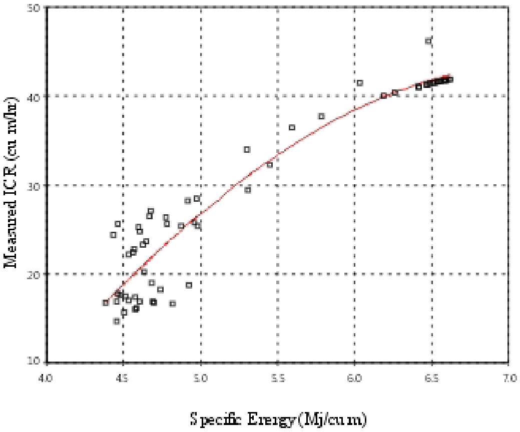

Figure 4. Relation between measured ICR and specific energy (R^2=0.91).

Table 4. Measured and predicted ICR with percentage of relative errors between them for all cutting cases (Continued)

Case No.	Measured instantaneous cutting rate (m^3/hr)	Predicted instantaneous cutting rate (with respect to alpha angle) (m^3/hr)	Relative error between measured and predicted instantaneous cutting rate (with respect to alpha angle) (%)	Predicted instantaneous cutting rate (with respect to specific energy) (m^3/hr)	Relative error between measured and predicted instantaneous cutting rate (with respect to specific energy) (%)
1	22.2	21.5	0.032	19.3	0.131
2	25.3	25.1	0.008	20.4	0.192
3	24.8	25.4	0.022	20.6	0.170
4	23.7	21.4	0.096	21.3	0.103
5	23.2	21.6	0.070	20.9	0.100
6	22.8	21.2	0.071	19.9	0.125
7	27.1	24.1	0.108	21.8	0.195
8	25.7	22.9	0.108	18.1	0.293
9	25.6	24.6	0.038	23.5	0.082
10	20.2	20.4	0.011	21.1	0.041
11	28.2	24.5	0.132	25.5	0.095
12	24.4	21.8	0.109	17.7	0.276
13	26.4	23.9	0.095	21.6	0.182
14	25.7	23.1	0.101	26.2	0.018

Case No.	Measured instantaneous cutting rate (m^3/hr)	Predicted instantaneous cutting rate (with respect to alpha angle) (m^3/hr)	Relative error between measured and predicted instantaneous cutting rate (with respect to alpha angle) (%)	Predicted instantaneous cutting rate (with respect to specific energy) (m^3/hr)	Relative error between measured and predicted instantaneous cutting rate (with respect to specific energy) (%)
15	41.5	40.1	0.033	38.7	0.067
16	46.2	46.0	0.004	41.7	0.097
17	32.2	29.4	0.088	32.8	0.017
18	16.7	17.8	0.062	16.7	0.001
19	17.4	19.9	0.140	20.1	0.153
20	16.8	18.2	0.081	18.0	0.068
21	17.0	18.7	0.096	19.4	0.137
22	17.5	19.4	0.107	19.0	0.083
23	16.8	18.5	0.101	22.0	0.307
24	16.7	17.4	0.045	24.0	0.443
25	16.1	18.4	0.141	20.2	0.252
26	17.7	19.0	0.074	18.3	0.039
27	16.0	17.7	0.107	20.2	0.260
28	17.0	18.2	0.074	20.6	0.213
29	14.6	17.1	0.169	18.1	0.233
30	19.0	21.2	0.113	21.9	0.148
31	17.7	18.7	0.055	18.1	0.022
32	15.7	17.8	0.131	18.8	0.198
33	18.7	21.0	0.119	25.7	0.369
34	16.8	17.9	0.064	22.1	0.315
35	18.3	21.0	0.149	22.8	0.250
36	26.4	25.2	0.046	23.4	0.114
37	25.3	26.8	0.060	24.9	0.015
38	28.5	26.6	0.065	26.4	0.074
39	25.4	26.9	0.058	26.5	0.042
40	29.4	27.8	0.055	31.0	0.055
41	22.4	21.2	0.053	19.9	0.110
42	36.4	34.7	0.046	34.4	0.054

Case No.	Measured instantaneous cutting rate (m³/hr)	Predicted instantaneous cutting rate (with respect to alpha angle) (m³/hr)	Relative error between measured and predicted instantaneous cutting rate (with respect to alpha angle) (%)	Predicted instantaneous cutting rate (with respect to specific energy) (m³/hr)	Relative error between measured and predicted instantaneous cutting rate (with respect to specific energy) (%)
43	37.7	36.7	0.027	36.5	0.034
44	40.4	41.9	0.039	40.4	0.002
45	41.1	42.8	0.041	41.4	0.008
46	41.1	42.8	0.041	41.4	0.008
47	41.4	43.4	0.049	41.7	0.009
48	41.6	43.9	0.055	42.0	0.010
49	41.8	44.9	0.075	42.2	0.011
50	34.0	32.3	0.049	31.0	0.089
51	40.0	38.9	0.029	39.9	0.002
52	41.3	42.0	0.017	41.6	0.009
53	41.3	39.6	0.040	41.7	0.009
54	41.5	35.8	0.137	41.9	0.010
55	41.5	37.1	0.106	41.9	0.010
56	41.6	39.7	0.046	42.0	0.010
57	41.7	44.7	0.072	42.1	0.010
58	41.8	44.2	0.059	42.2	0.011
59	41.8	39.5	0.054	42.3	0.011
60	41.9	38.5	0.081	42.3	0.011
61	41.8	44.9	0.074	42.2	0.011
62	41.9	45.2	0.078	42.4	0.011

Table 5. Typical specifications of DOSCO MD 1100 roadheaders (Dosco Ltd, 2008)

Model Type	R [a]	R²	Adjusted R²	Std. error of the estimation
Cubic (linear)	0.95	0.91	0.91	3.12202

Dependent variable: Measured ICR (m³/hr)

a. Predictors: (Constant), SE (MJ/m³)

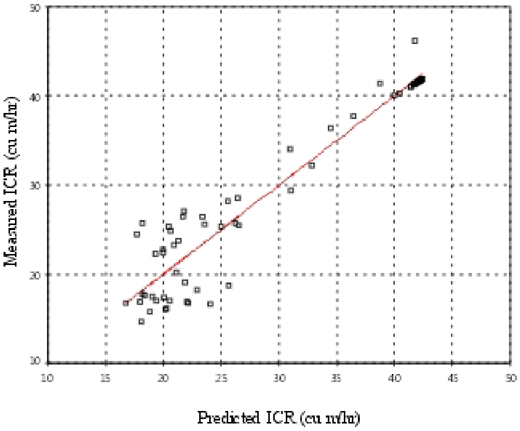

Figure 5. Linear regression between measured ICR and predicted ICR (with respect to specific energy) (R^2=0.91).

DISCUSSIONS

The second model (Equation 17) has been developed only based on SE. It is due to investigate the relation between ICR and SE to gain in which ICR value, the specific energy represents the minimum value. Having this ICR and its corresponding RMBI, the α angle can be calculated using Equation 16. As a consequence, the excavation routs should be designed on the basis of this value to yield maximum cutting performance (minimum specific energy). It should be noticed that the optimum SE can be best measured by utilizing linear cutting machine but because of lack of the equipment, specific energy determined using Equation 15. Moreover, it should be kept in mind that findings with the alpha angle that is investigated for axial (milling) type head as in this work may not be fully considered for transverse type roadheaders, due to the fact that the cutting position of each cutting head is orientated differently with respect to the tunnel axis.

Utmost care should be paid when considering cutting head power of roadheaders for performance predictions, as roadheaders with different cutting head type are also seen to perform differently. Machines with transverse (ripping) type cutting heads generally have higher motor power and lower weight, while the opposite is true for those of axial type. An ICR value obtained with a transverse machine, may also be achieved by a similar size milling (axial) type machine, all operating in similar conditions, i.e. machines are likely to perform the same duty despite having different cutting head motor power. It is, therefore, important to mention that the findings in this work are suitable to predict the performance of medium-duty roadheaders fitted with axial cutting head. In performance prediction, many authors discard the cutting head design. Previous works (Hekimoglu and Fowell, 1990; Hekimoglu, 1995; Hekimoglu et al., 2003; Hekimoglu and Ozdemir, 2004) clearly showed that under the identical conditions, the cutting performance of mechanical excavators such as roadheaders and coal shearers dramatically increased with a modification in their cutting head/drum design.

CONCLUSIONS

Primarily, field investigations were conducted in order to determine the geomechanical properties and machine performance in the Tabas coal mine project. Special attentions were made on determining the influence of discontinuity orientation and specific energy of the coal measure rocks on the performance of roadheaders. With this respect, the alpha angle (the angle between the tunnel axis and the planes of weakness) and the specific energy (the work to excavate a unit volume of rock) were determined for each cutting case. The instantaneous cutting rates (the machine performance) were also measured for each cutting case. Subsequently, a database regarding the required parameters was established. The statistical analysis was then utilized to establish relations between the ICR and various parameters of the database. With this respect, two new performance predictive models (with respect to alpha angle and the specific energy) were developed. The comparison between the measured and the predicted ICR using the two developed models show to have a good correlations. However, it is observed that the correlation for the model utilizing the alpha parameter is higher (R^2=0.96) than the model using the specific energy (R^2=0.91). Within the measured variables and available conditions, the predictive models established in this work for ICR may successfully be used for performance prediction of medium-duty roadheaders of axial (milling) type operating in coal measure rocks.

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