Predicting "cuttability" with surface miners - A rockmass classification approach

Dey, K.[a], Ghose, A.K.[b]

[a] National Institute of Technology, Rourkela, 769008
[b] Indian School of Mines University, Dhanbad

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Predicting "Cuttability" with Surface Miners – A Rockmass Classification Approach

Kaushik Dey* and A. K. Ghose**

*Lecturer, National Institute of Technology, Rourkela, India - 769008, Email – kausdey@yahoo.co.uk
**Former Director, Indian School of Mines, Dhanbad, Email – ghose.ajoy@gmail.com

ABSTRACT

Surface miners made their debut in Indian surface mining industry in 1996. Presently, around 105 surface miners are working in Indian coal and limestone mines. The surface miners are being deployed largely on trial and error basis and the investors are interested in field experimental runs. Manufacturers evaluated the applicability of surface miners based on compressive strength of rock. In this context, it is logical to establish a suitable cuttability index to predict the performance of surface miners. In this present paper, the existing cuttability indices are reviewed and a new cuttability index proposed. A new relationship is also proposed to predict the output from surface miners using the cuttability index.

INTRODUCTION

Development of surface miner was initiated in 1970s and was continued into the early 1980s and marks a new paradigm in surface mining system (Ghose, 2008)[1]. The design concept for the surface miner is based on the milling principle and owes its origin to the road milling machines which cuts the old road surface for road construction. Since 1990s, surface miners have gained in popularity with improved design of cutting drum and higher machine power. This has enabled the users to excavate rock from insitu with competitive cost and eco-friendliness. Viability of a mining project rests upon the appropriate selection of rock excavation system right from the planning stage. This choice must be based on – (i) understanding of the characteristics of rockmass, (ii) required product characteristics (mainly, size and grade) and (iii) selection of suitable equipment (especially, the excavating machine) (Dey, 1999)[2]. For economical rock excavation, therefore, using surface miners, there are two basic elements to be considered – the machine and the rockmass. A machine is the product of human ingenuity and can be modified to suit a specific requirement (Eskikaya S. and Tuncdemir H., 2007)[3].

However, rockmass is a natural component in the earth's crust and is thus immutable. It is imperative, therefore, to understand the rock to be excavated prior to selection of the machine. The contribution seeks to present a rational basis for evaluating the applicability of surface miner using rockmass classification system.

REVIEW

"Cuttability" of a surface miner depends on a number of influencing parameters. These parameters can be categorized as rock/rockmass parameters, machine parameters and the type of application. The properties relevant to the classifications are detailed in Table 1.

Table 1: Parameters influencing cuttability of surface miner

Rock/rockmass parameters	Machine configuration	Type of Application
Moisture content, density, brittleness, unconfined compressive strength, point load index, Young's modulus, fracture energy, toughness index, Brazilian tensile strength, sonic velocity, abrasivity (Schimazek-F, Cerchar) volumetric joint count, stickiness of material, specific energy of cuttability	Cutting tool configuration (rake angle, attack angle, clearance angle and tip angle, pick lacing, type of pick (point attack) number of picks, tip material), drum weight, engine power, nature of coolant for tips	Mode of operation (windrowing/ conveyor loading), length and width of operating area (select machine travel method), operator skill, specific requirements (dry/wet, fragmentation desired and output)

Rockmass classification forms the backbone of empirical design approach, it is necessary to recognize the caveats implicit in its application (Ghose, 1996)[4]. The existing rockmass classification systems available for prediction of suitability of mechanical excavation are reviewed here. The pioneering system of this type of classification was the Discontinue Strength Classification (Franklin et. al., 1971)[5]. This was followed by Rippability Rating Chart (Weaver, 1975)[6], Excavation Index (Kirsten, 1982)[7], Geological Factors Rating Scale (Minty and Kearns, 1983)[8], Engineering Classification of Coal Measures (Scoble and Moftuoglu, 1984)[9], Rippability Chart (Singh et. al., 1986)[10], Excavatability Index Rating Scheme (Hadjigeorgiou and Scoble, 1990)[11], Diggability Index (Karpuz, 1990)[12], Revised Excavatability Graph (Pettifer and Fookes, 1994)[13] and many more. The manufacturers of the surface miners compute performance curves mostly based on the Unconfined Compressive Strength (UCS) or the ratio of compressive and tensile strengths. These indices have been used either directly or indirectly to select appropriate excavation systems, the equipment used in mining and assessment of the excavatability (Kramdibrata, 1998)[14].

Barendsen (1970)[15] developed a relationship (Figure 1) between specific energy and uniaxial compressive strength for the machines working with cutting (drag bit) and crushing (rotary bit) principles respectively.

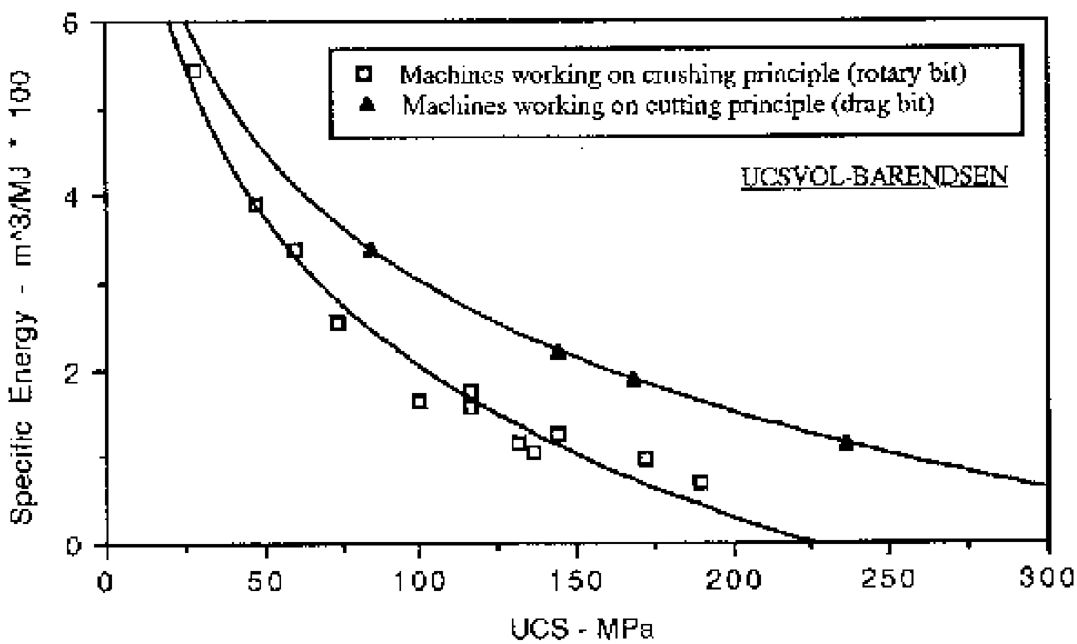

Figure 1 – Prediction of specific energy required for cutting (Barendsen, 1970)

Atkinson (1971)[16] was the first to classify the excavability of the rockmass based on the field seismic velocity measurement as in Figure 2. However, this only gives an idea of "GO – NO GO" situation.

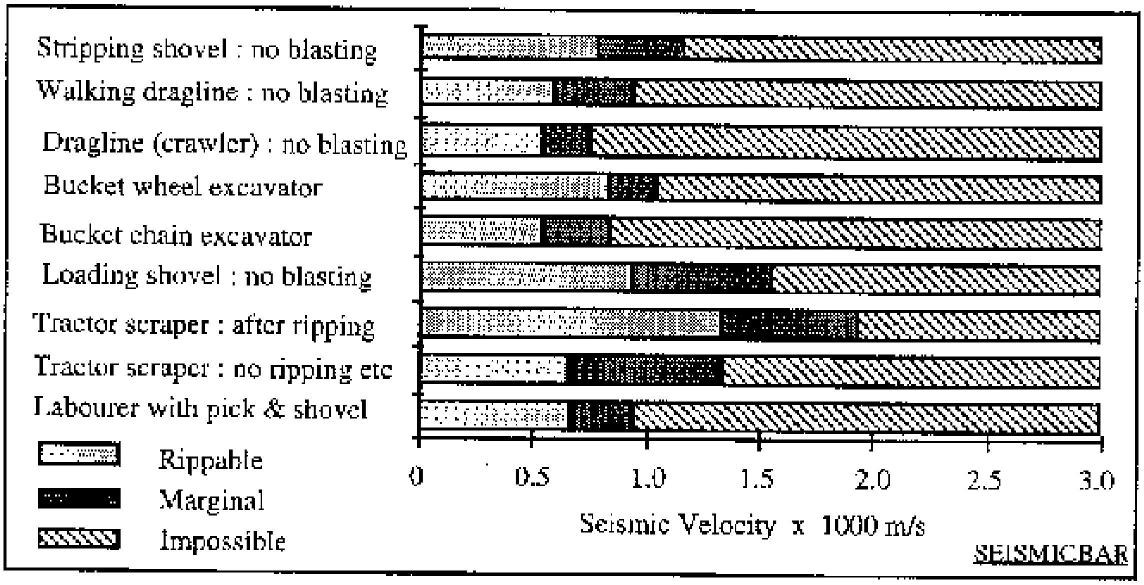

Figure 2 – Determination of excavation possibilities (Atkinson, 1971)

Rasper (1975)[17] proposed the following formula to calculate the cutting power required for bucket wheel excavator –

$$N_c = \frac{0.0054}{\eta} F_L \, (L^* \, n_s \, R)^{0.5} \tag{1}$$

where,

N_c = cutting drive power (kW)

η = efficiency

F_L= linear specific cutting resistance (kN/m)

L^* = production (bcm/h)

n_s = number of bucket discharge per minute

R = radius of the wheel (m).

Graham (1976)[18] developed an empirical equation to predict the penetration rate of the tunnel boring machine (TBM) for known UCS values utilizing the experience of the TBM manufacturer –

$$P = \frac{3940 \, F_c}{\sigma_c} \tag{2}$$

where,

P = penetration rate (mm/rev)

F_c = average cutter force (kN)

σ_c = unconfined compressive strength (kN/m^2).

Farmer and Glossop (1980)[19] modified Graham's formula by replacing compressive strength with the tensile strength value in arriving at the penetration rate of TBM as given below -

$$P = \frac{624\, F_c}{\sigma_t} \tag{3}$$

where,

P = penetration rate (mm/rev)

F_c = average cutter force (kN)

σ_t = indirect tensile strength (kN/m^2).

Kirsten (1982)[7] identified the parameters influencing the excavatability of the rock, namely, strength of rock, in-situ rock density, degree of weathering, seismic velocity, block size, shape of excavation relative to excavating equipment, block shape, block orientation, joint roughness, joint gouge, joint separation. Kirsten formulated an Excavatability Index, a similar system like NGI 'Q' Index, as below –

$$N = M_s \frac{RQD}{J_n} J_s \frac{J_r}{J_a} \tag{4}$$

where,

N = excavatability index

M_s = mass strength number

RQD = rock quality designation

J_n = joint set number of Q - system

J_s = relative ground structure number

J_r = joint roughness number of Q - system

J_a = joint alteration number of Q - system

According to Kirsten, the rippability can be assessed as given in Table 2.

Table 2 – Assessment of rippability based on excavatability index (Kirsten, 1982)

Excavatability index	Possibility of ripping
$1 < N < 10$	Easy ripping
$10 < N < 100$	Hard ripping
$100 < N < 1000$	Very hard ripping
$1000 < N < 10000$	Extremely hard ripping/advised blasting
$N > 10000$	Blasting

Huges (1986)[20] established that the advance rate of full-face tunneling machines with disc cutter is a function of thrust per disc, speed of cutting, average number of disc per kerf, average radius of disc and unconfined compressive strength. The relationship proposed is given as,

$$P = \frac{6\, F_t^{1.2} \varpi\, n}{\sigma_c^{1.2}\, r^{0.6}} \tag{5}$$

where,

P = penetration rate (m/h)

F_t = thrust per disc periphery (kN)

ω = speed of cutting head (rev/sec)

n = average number of disc per kerf

r = average radius of disc (m)

σ_t = unconfined compressive strength (MPa).

Singh et. al. (1986)[10] used *Toughness Index* (TI), which is believed to be a measure of elastic strain energy requirements for deforming using a cutting tool and is derived from UCS and Young's modulus as given below -

$$TI = \frac{\sigma_c^{\,2}}{2\,E} \times 100 \tag{6}$$

where,

TI = toughness index (MPa)

E = Young's modulus (GPa)

σ_c = unconfined compressive strength (MPa).

Similarly, Farmer (1986)[21] proposed fracture index or rock toughness, which is defined as the strain energy required to fracture the rock and is estimated as –

$$EI = \frac{\sigma_c^{\ 2}}{E} = \frac{N\,\eta}{L^*} \tag{7}$$

where,

EI = energy input

N = power (kW)

η = efficiency

L^* = production (bcm/h)

E = Young's modulus (GPa)

σ_c = unconfined compressive strength (MPa).

Farmer also developed a performance prediction curve for DOSCO-IIIA machine in coal measure rocks as shown in Figure 3.

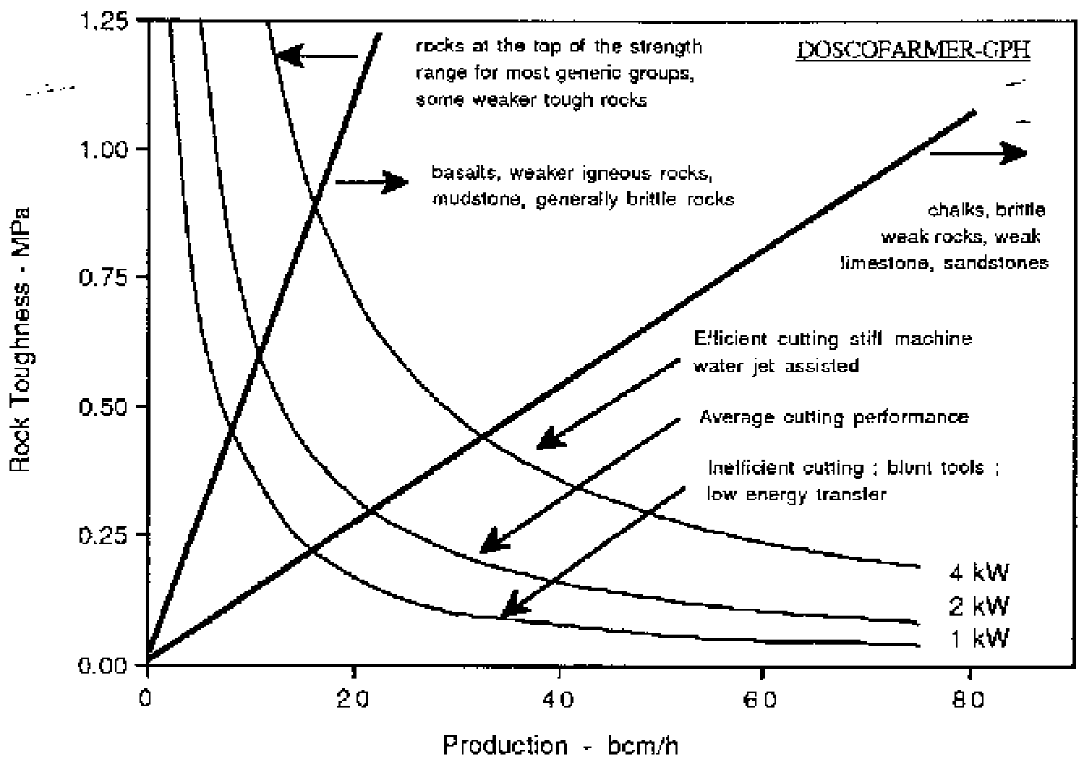

Figure 3 – Relationship between rock toughness and volume extraction rate based on machine-rock energy transfer (after Farmer, 1986)

Roxborough (1987)[22] utilized specific energy derived from instrumental cutting test (core cuttability test) to relate performance of medium/heavy weight road headers (Table 3).

Table 3 – Selection of roadheader based on laboratory specific energy test

Upper value of laboratory specific energy (MJ/m^3)		Generalized cutting performance
Heavy weight machine	**Medium weight machine**	
25 – 32	15 – 20	Machine can cut economically if occurs in thin bed (< 0.3 m)
20 – 25	12 – 15	Poor cutting performance. Point attack tool may be more beneficial and low speed cutting motor will improve stability.
17 – 20	8 – 12	Moderate to poor performance. For abrasive rocks frequent pick change is required
8 – 17	5 – 8	Moderate to good cutting performance with low machine wear.
< 8	< 5	High advance rate and high productivity

Bilgin et al. (1988)[23] estimated the advance rate of a roadheader using UCS and rock quality designation (RQD). The proposed a rockmass cuttability index (RMCI), was defined as –

$$RMCI = \sigma_c \left(\frac{RQD}{100} \right)^{2/3} \qquad (8)$$

where,

$RMCI$ = rockmass cuttability index (kg/cm^2)

RQD = rock quality designation (%)

σ_c = unconfined compressive strength (kg/cm^2).

A relationship between advance rate of a roadheader of cutting power less than 100HP against rockmass cuttability index was derived and is shown in Figure 4.

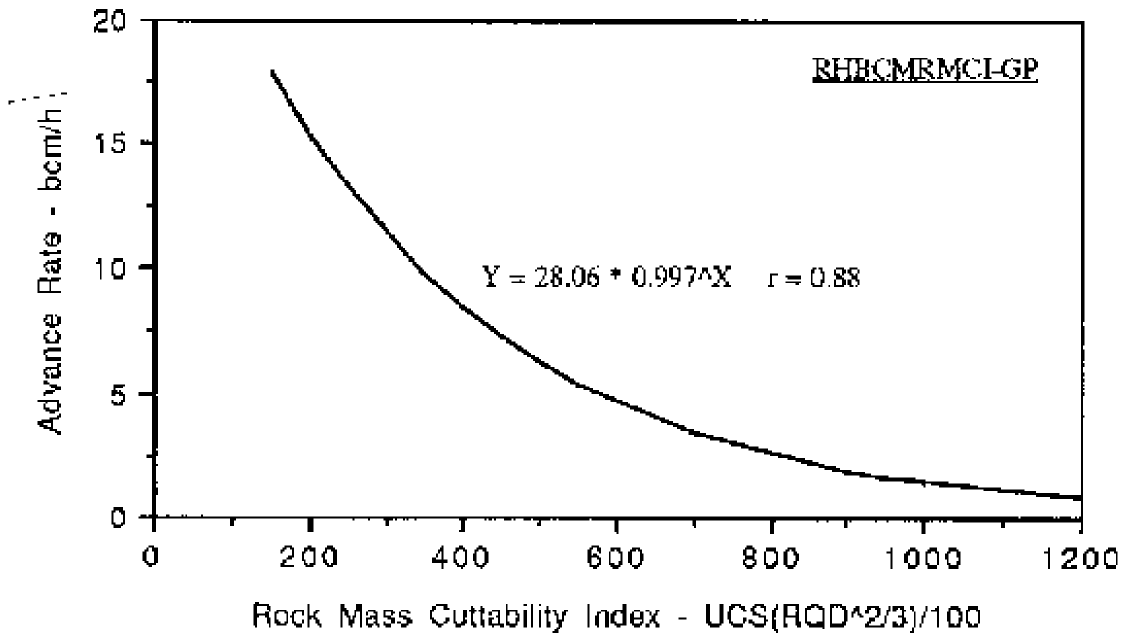

Figure 4 – Relationship between advance rate of roadheader and RMCI (Bilgin et al., 1988)

Gehring (1989)[24] proposed that the performance of a roadheader (rock cutting machine) could be defined as –

$$L^* = \frac{k}{\sigma_c} N \tag{9}$$

where,

L^* = production or cutting performance (bcm/h)

N = cutter head power (kW)

k = a factor for consideration of relative cuttability or tuning effect between road header and rock

σ_c = unconfined compressive strength (MPa).

In 1992, Gehring[25] modified his earlier formula for use of VASM-2D as follows:

$$L^* = \frac{k_1 \times k_2 \times k_3}{\sigma_c} N \tag{10}$$

where,

k_1 = relative cuttability of intact rock and,

= 6 for very tough and plastic rock

= 7 for tough and plastic rock

= 8 for average rock

= 9 for brittle rock

= 10 for very brittle rock

= 10 – 15 for coal

k_2 = influence of discontinuity such as joint, bedding plane etc and,

= 1 for massive and discontinuity distance > 25 cm

= 1.5 – 2 for layered/fissured, thinner bed rock, discontinuity 10 – 25 cm

= 2.5 for layered/fissured/interbedded rock discontinuity <5 cm

k_3 = influence of specific cutting condition and is a function of no sumping, cutting height, cuter head oscillation, pick array, pick shape. However, for roadheader its value ranged from 3.5 – 4.5.

Gehring[26] classified rock for application of TBM and roadheader based on the Voest-Alpine Rock Cuttability Index (VARCI) as given in Table 4.

Table 4 – Selection of TBM and roadheader based on VARCI (Gehring, 1980)

VARCI (mm)	Cuttability with TBM	Cuttability with roadheader
<0.5	Moderate performance	Not applicable
0.5 - 0.8	Fair to good performance	Applicable only when rock occurs in thin single layer
0.8 – 1.5	Best range of application	Cuttable with heavy machines and strong conical picks
1.5 – 2.5	Only TBM with disc cutters	Medium weight machines with conical picks
2.5 – 5.0	Wheels with conical picks, disc cutters for abrasive rock	Medium and light weight machines, conical picks/drag type picks, best range of application
5.0 – 10.0	Application of TBM only in shielded version with drag picks	Medium and light weight machines, slim conical and drag type picks

Note: Heavy and medium duty roadheader means 50 – 80 tons class and 23 – 50 tons class respectively, Hadjigeorgiou and Scoble (1990)[27] developed an excavation index classification scheme and correlate it with other excavation indices. The index was developed using some rock and geologic parameters as rated below –

$$EI = (I_s + B_s)\, W\, J_s$$

where,

EI = Excavation Index

I_s = point load strength index

B_s = block size index

W = weathering index

J_s = relative ground structure index.

The above-mentioned excavating index rating scheme is detailed in Table 5.

Table 5 – Excavating index rating scheme

Class	**I**	**II**	**III**	**IV**	**V**
Point load index	< 0.5	0.5 – 1.5	1.5 – 2.0	2.0 – 3.5	> 3.5
Rating (I_s)	0	10	15	20	25
Volumetric joint count	> 30	30– 10	10 – 3	3 – 1	1
Rating (B_s)	5	15	30	45	50
Weathering	completely	highly	moderately	slightly	unweathered
Rating (W)	0.6	0.7	0.8	0.9	1.0
Relative ground structure	very favourable	favourable	slightly unfavourable	unfavourable	very unfavourable
Rating (J_s)	0.5	0.7	1.0	1.3	1.5

Thuro (2003)[28] utilized 'specific destruction work' (W_z) to predict the cutting performance of a roadheader. This 'specific destruction work' is the work done required to fragment the rock (or energy required to create new surface area) and is expressed in KJ/m^3.

Einstein et al. (1979)[29] provided a neat critique of expectations of classification system as follows –

"*(1) they should promote economical and yet safe design,* *(2) they must be correctly calibrated against test cases and those test cases must be representative of the field application for future use,*

(3) they should be complete in that all relevant factors are included, yet they must be practical in that parameters can be determined and with acceptable certainty,

(4) they should have general applicability and robustness to the vagaries of use, yet they must be recognized as fundamentally subjective."

In addition to the above, Ghose (1996)[4] posited "*there has been no dearth of efforts in adding sophistry to the essential simplistic elegance of classification systems and removing its subjectivity*".

CUTTABILITY CLASSIFICATION FOR SURFACE MINERS – A PROPOSAL

A new rockmass classification system is simplistically developed considering the key influencing parameters, namely, point load strength index and volumetric joint count. Influence of rock abrasivity and direction of machine operation with respect to joint direction are also considered. Considering the high power machine can cut a relatively stronger rock, the engine power of the cutting machine is also rated in this classification. The rating of these parameters are tabulated below –

Table 6 – Rating of the parameters of new rockmass cuttability classification

Class	I	II	III	IV	V
Point load index (I_s50)	< 0.5	0.5 – 1.5	1.5 – 2.0	2.0 – 3.5	> 3.5
Rating (I_s)	5	10	15	20	25
Volumetric joint count (no/m^3)	> 30	30– 10	10 – 3	3 – 1	1
Rating (J_v)	5	10	15	20	25
Abrasivity	< 0.5	0.5 – 1.0	1.0 – 2.0	2.0 – 3.0	> 3.0
Rating (A_w)	3	6	9	12	15
Direction of cutting respect to major joint direction	72^0 - 90^0	54^0 - 72^0	36^0 - 54^0	18^0 - 36^0	0^0 - 18^0
Rating (J_s)	3	6	9	12	15
Machine power (kW)	> 1000	800 – 1000	600 – 800	400 – 600	< 400
Rating (M)	4	8	12	16	20

Thus, the new cuttability index is the sum of the rating of above five parameters –

$$CI = I_s + J_v + A_w + J_s + M \quad (11)$$

If the point load index is obtained from sample of diameter other than 50 mm a size correction factor may be incorporated (Greminger, 1982)[30] and is given below –

$$I_s 50 = F\, I_s \quad (12)$$

where,

F = (diameter of sample/50)$^{0.45}$

The abrasivity considered here is Cerchar abrasivity as described by West (1989)[31] using a test pick and stereo-microscope with ocular micrometer. Volumetric joint count can either be measured direct in the field or be estimated from *RQD* as proposed by Palmström (1985)[32]:

$$RQD = 115 - 3.3\, J_v \quad (13)$$

Based on this new cuttability classification, the ease of excavation of rockmass using surface miner can be classified as given below -

Table 7 – Assessment of excavatability of surface miner based on cuttability index

Excavatability index	Possibility of ripping
$50 > CI$	Very easy excavation
$50 < CI < 60$	Easy excavation
$60 < CI < 70$	Economic excavation
$70 < CI < 80$	Difficult excavation, may be not economic
$CI > 80$	Surface miner should not be deployed

The proposed cuttability index is easy to derive and gives a first hand idea about the "GO – NO GO" criterion on applicability of surface miner. The main advantage of this cuttability index is that it considers the cutting power of the machine. With heavy machines of higher cutting power, surface miner could be applied for higher rock strengths also. While considering the economics of the application, abrasivity of the rock or in turn the wear to the point attack cutting tools, has significant influence. This aspect is also incorporated in this cuttability index.

Production rate of a surface miner can be estimated as follow –

$$L^* = \left(1 - \frac{CI}{100}\right) k M_c \quad (14)$$

where,

L^* = production or cutting performance (bcm/h)

M_c = Rated capacity of the machine (bcm/h)

CI = cuttability index

k = a factor for consideration of influence of specific cutting condition and is a function of pick lacing (array), pick shape, atmospheric condition etc. and varies from 0.5 – 1.0.

CASE STUDIES

The field investigations have been carried out in three sites – two in limestone and one in coal. The details of the investigations are given below –

<u>Coal mines:</u>

Field investigations were carried out at Lakhanpur Opencast Project of Mahanadi Coal Fields Limited. The coal properties are as follows:

Point load index = 1.1 i.e. rating I_s = 10

Surface Miner used == 2100 SM

Rated machine capacity = 400 m^3/h

Machine power = 448 kW i.e. rating M_c = 16

Volumetric joint count = 32 i.e. rating J_v = 5

Abrasivity = 0.4 i.e. rating I_s = 3

Direction of machine operation with respect to joint plane = 80^0 i.e. rating J_s = 3

Thus, cuttability index (CI) = 37 **(thus very easy cutting condition for surface miner)**

Expected production (for k = 0.6) = (1 – 37/100) × 400 × 0.6 = 151 m^3/h

Density = 1.4

Expected production achieved = 210 t/h

Actual production achieved = 225 t/h

<u>Limestone mines:</u>

Field investigations were carried out at Adanakuruchi Limestone Mines of India Cement Limited. The rock properties are as follows:

Point load index = 2.1 i.e. rating I_s = 20

Surface Miner used == 2100 SM

Rated machine capacity = 400 m^3/h

Machine power = 448 kW i.e. rating M_c = 16

Volumetric joint count = 20 i.e. rating J_v = 10

Abrasivity = 1.5 i.e. rating I_s = 9

Direction of machine operation with respect to joint plane = 86^0 i.e. rating J_s = 3

Thus, cuttability index (*CI*) = 58 **(thus easy cutting condition for surface miner)**

Expected production (for k = 0.5) = (1 – 58/100) × 400 × 0.5 = 84 m^3/h

Density = 2.2

Expected production achieved = 184 t/h

Actual production achieved = 143 t/h

<u>Hard limestone mines</u>:

Field investigations were carried out at Limestone Mines of Madras Cement Limited. The rock properties are as follows:

Point load index = 2.7 i.e. rating I_s = 20

Surface Miner used == 2600 SM

Rated machine capacity = 600 m^3/h

Machine power = 559 kW i.e. rating M_c = 16

Volumetric joint count = 10 i.e. rating J_v = 15

Abrasivity = 1.5 i.e. rating I_s = 9

Direction of machine operation with respect to joint plane = 90^0 i.e. rating J_s = 3

Thus, cuttability index (*CI*) = 63 **(thus economic cutting condition for surface miner)**

Expected production (for k = 0.5) = (1 – 63/100) × 600 × 0.5 = 111 m^3/h

Density = 2.2

Expected production achieved = 244 t/h

Actual production achieved = 210 t/h

The expected performance of different surface miners for rock type similar to Adanakuruchi limestone mines of India Cement Limited (case study – 2) are computed and is presented in Table 8.

Table 8 – Expected performance of different surface miners

Model	Performance
SM2100	84 m^3/h
SM2600	126 m^3/h
SM3500	375 m^3/h
SM3700	540 m^3/h
SM4200	594 m^3/h

CONCLUSIONS

The new cuttability index should provide a handy tool for decision making on the applicability of surface miners. The extension of Gehring's formula for prediction of production rate of surface miners is acceptable with reasonable accuracy. Determination of the new cuttability index is simple and gives reasonable accuracy.

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