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Review of Cuttability Indices and A New Rockmass Classification Approach for Selection of Surface Miners

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Abstract Rock excavation is carried out either by drilling and blasting or using rock-cutting machines like rippers, bucket wheel excavators, surface miners, road headers etc. Economics of mechanised rock excavation by rock-cutting machines largely depends on the achieved production rates. Thus, assessment of the performance (productivity) is important prior to deploying a rock-cutting machine. In doing so, several researchers have classified rockmass in different ways and have developed cuttability indices to correlate machine performance directly. However, most of these indices were developed to assess the performance of road headers/tunnel-boring machines apart from a few that were developed in the earlier days when the ripper was a popular excavating equipment. Presently, around 400 surface miners are in operation around the world amongst which, 105 are in India. Until now, no rockmass classification system is available to assess the performance of surface miners. Surface miners are being deployed largely on trial and error basis or based on the performance charts provided by the manufacturer. 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 indexes proposed. A new relationship is also developed to predict the output from surface miners using the proposed cuttability index.

Keywords Cuttability · Surface miner · Rockmass classification

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1 Introduction

The surface miner was developed in the mid-70s improving the design concept of the road milling machine, which were popularly used to cut the old road surface during road construction (Dey 1999). The surface miner essentially comprises a cutting unit, disposing unit (windrowing/conveyor loading) and propelling unit (Fig. 1a). The surface miner is a track mounted machine, it is mounted either on three or four tracks depending on the type of model. Each set of crawler unit has a separate steering cylinder to ensure sharp turns. It has a powerful diesel engine and hydraulic pumps for transmitting the power for different operations. The heart of the surface miner is the milling drum, which cuts and loads the material onto the primary conveyor. The milling drum is fitted with specially manufactured tungsten carbide tipped steel cutting tools mounted in tool holders. There are 70–120 cutting picks depending on the machine application and type of model. The tool holders are arranged on the milling drum in a spiral fashion. The milling drum rotates in an up milling direction and a layer of predetermined thickness of the deposit is cut and crushed to the optimal size by the cutting tools. Depth of cut is controlled by the "electronic depth control system" which enables the milling drum to achieve the preset cutting depth. The rock is excavated by the milling drum utilizing the combination of normal force and drag force. Angle of attack of the pick is important as shown in Fig. 1b. As per the rule of thumb, the clearance angle is kept less around 5° and rake angle is kept around 25°. Depth of cut is important for determining the theoretical output (depth of cut × drum width × velocity of movement) of surface miner. However, depth of cut depends on the drum diameter, machine power, and type of material. With the increase in the depth of cut, load on the machine increases, which in turn, decreases the speed of the machine.

Since the 1990s, surface miners have gained in popularity with improved design of the cutting drum and higher machine power. This has enabled the users to excavate rock from in situ with competitive cost and eco-friendliness. Surface miners can be classified in three categories based on the principle of rock cutting, namely, (1) cutting drum positioned in front of the machine, (2) cutting drum positioned below the machine and rotate in up-cutting direction and (3) cutting drum positioned below the machine and rotate in a complementary direction. Among these, the second model is the most popular and its cutting system is given in Fig. 1a. Keeping the cutting drum below the machine has the added advantage that it utilizes machine weight in cutting of the rock.

For economical rock excavation, therefore, using surface miners, two basic elements should 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 and Tuncdemir 2007). However, a rockmass is a natural component in the earth's crust and is thus immutable. Therefore, it is imperative to understand the rock to be excavated prior to selecting the machine. This contribution seeks to present a rational basis for evaluating the applicability of surface miners using a rockmass classification system.

2 Cuttability Indices–A Review

"Cuttability" of a surface miner depends on a host 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.

Rockmass classification forms the backbone of the empirical design approach. It is necessary to recognize the

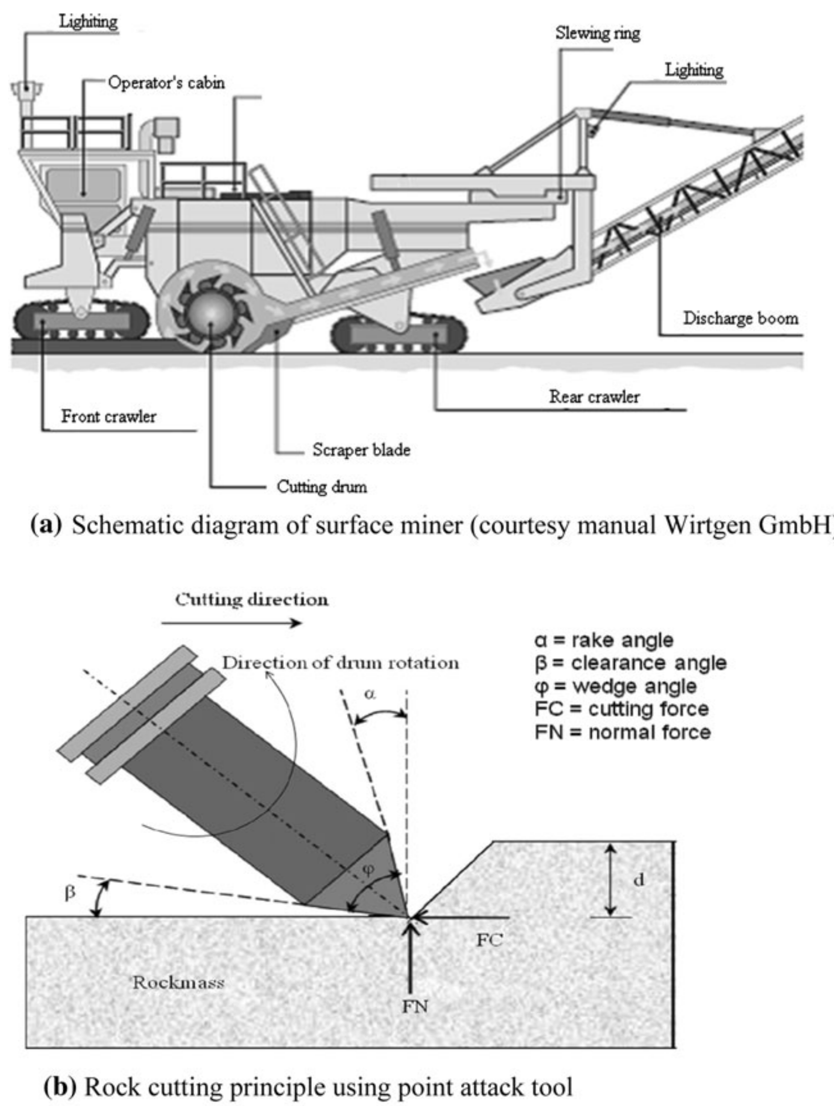

Fig. 1 Schematic diagram of surface miner and theory of rock cutting (**a**) Schematic diagram of surface miner (courtesy manual Wirtgen GmbH) (**b**) Rock-cutting principle using point attack tool

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)

caveats implicit in its application (Ghose 1996). 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 Discontinuity Strength Classification (Franklin et al. 1971). This was followed by a Rippability Rating Chart (Weaver 1975), Excavation Index (Kirsten 1982), Geological Factors Rating Scale (Minty and Kearns 1983), Engineering Classification of Coal Measures (Scoble and Muftuoglu 1984), Rippability Chart (Singh et al. 1986), Excavatability Index Rating Scheme (Hadjigeorgiou and Scoble 1990), Diggability Index (Karpuz 1990), Revised Excavatability Graph (Pettifer and Fookes 1994) 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).

2.1 Cuttability Indices for Cutting with Drag Pick

Barendsen (1970) developed a relationship (Fig. 2) between specific energy and uniaxial compressive strength for the machines working with cutting (drag bit) and crushing (rotary bit) principles, respectively.

Atkinson (1971) was the first to classify the excavability of the rockmass based on the field seismic velocity measurement as in Fig. 3. However, this only gives an idea of the "GO–NO GO" situation.

Rasper (1975) proposed the following formula to calculate the cutting power required for bucket wheel excavators

$$N_c = \frac{0.0054}{\eta} F_L \left(L^* n_s R\right)^{0.5} \quad (1)$$

where,

N_c = cutting drive power (kW)
η = efficiency
F_L = linear specific cutting resistance (kN/m)
L^* = production (bcm/h)

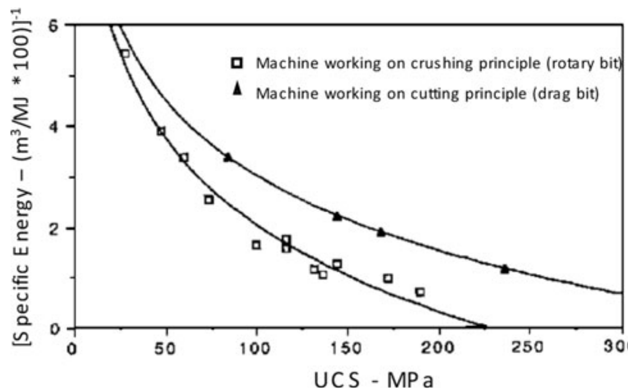

Fig. 2 Prediction of specific energy required for cutting (Barendsen 1970)

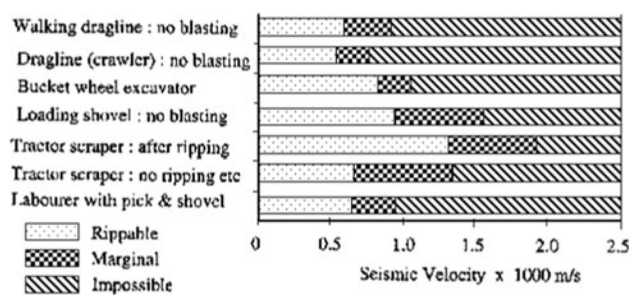

Fig. 3 Determination of excavation possibilities (Atkinson 1971)

n_s = number of bucket discharge per minute
R = radius of the wheel (m).

Singh et al. (1986) used the *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:

$$\mathrm{TI} = \frac{\sigma_c^2}{2E} \times 100 \quad (2)$$

where,

TI = toughness index (MPa)
E = Young's modulus (GPa)
σ_c = unconfined compressive strength (MPa).

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

$$\mathrm{EI} = \frac{\sigma_c^2}{E} = \frac{N\eta}{L^*} \quad (3)$$

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 Fig. 4.

Atkinson et al. (1986) used the toughness index, UCS and Young's modulus to classify the rock strength as shown in Table 2. He proposed that a toughness index of more than 27 represents un-economical cutting condition.

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

Bilgin et al. (1988) estimated the advance rate of a road header using UCS and rock quality designation (RQD). The proposed rockmass cuttability index (RMCI) was defined as:

$$\mathrm{RMCI} = \sigma_c \left(\frac{\mathrm{RQD}}{100}\right)^{2/3} \quad (4)$$

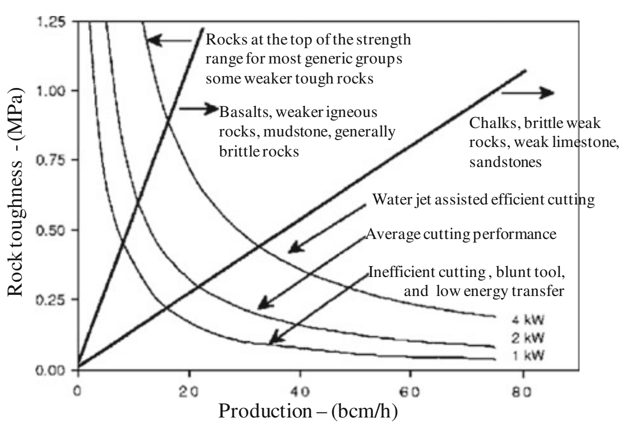

Fig. 4 Relationship between rock toughness and volume extraction (Farmer 1986)

Table 3 Selection of road header 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

where,

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

RQD = rock quality designation (%)

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

A relationship between the advance rate of a road header of cutting power less than 100HP against the rockmass cuttability index was derived and is shown in Fig. 5.

Gehring (1989) proposed that the performance of a road header (rock-cutting machine) could be defined as:

$$L^* = \frac{k}{\sigma_c} N \quad (5)$$

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 modified his earlier formula for use of Voest-Alpine Surface Miner (VASM-2D) as follows:

$$L^* = \frac{k_1 \times k_2 \times k_3}{\sigma_c} N \quad (6)$$

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

Table 2 Rock strength classification (Atkinson et al. 1986)

Rock type	UCS (MPa)	Young's modulus (GPa)	Toughness index
High strength	180.30	40	40.63
Medium strength	116.00	29	23.20
Low strength	58.51	13.36	12.81
Very low strength	29.92	7.76	5.77

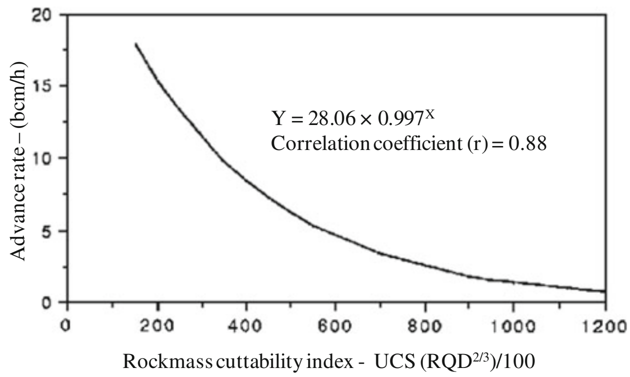

Fig. 5 Relationship between advance rate and RMCI (Bilgin et al. 1988)

= 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 dry/wet cutting, cutting height, cuter head flexibility, pick array, pick shape. However, for road header its value ranged from 3.5–4.5.

Gehring classified rock for application of TBMs and road headers based on the Voest-Alpine Rock Cuttability Index (VARCI) as given in Table 4.

Hadjigeorgiou and Scoble (1990) developed an excavation index classification scheme and correlated it with other excavation indices. The index was developed using some rock and geologic parameters as rated below:

$$\mathrm{EI} = (I_s + B_s)\, W\, J_s \qquad (7)$$

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.

Kolleth (1990) proposed an application range for excavators, scrapers, surface miners and bucket wheel excavators based on the compressive strength of rock samples (Fig. 6).

Natau et al. (1991) developed a correlation between the road header performance and UCS for brittle and non-plastic rocks as shown in Fig. 7.

Fowell and Johnson (1991) used a core cuttability test to determine the specific energy. A relationship, between the obtained specific energy and actual cutting rate in the field, has been developed for medium and heavy weight road headers (Fig. 8).

Bolukbasi et al. (1991) have also used laboratory-specific energy to describe diggability (Table 6).

Thuro (2003) utilized 'specific destruction work' (W_z) to predict the cutting performance of a road header. 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.

2.2 Cuttability Indices for Ripping

Franklin et al. (1971) developed a rockmass classification using the fracture index and the point load index. Different zones of ripping, digging, and blasting were shown in a plot of fracture index and point load index (Fig. 9).

Kirsten (1982) 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,

Table 4 Selection of TBM and road header based on VARCI (Gehring 1980)

VARCI (mm)	Cuttability with TBM	Cuttability with road header
<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

Heavy and medium duty road header means 50–80 ton class and 23–50 ton class, respectively

Table 5 Excavating index rating scheme

Class	I	II	III	IV	V
Point load index Rating (I_s)	<0.5	0.5–1.5	1.5–2.0	2.0–3.5	>3.5
	0	10	15	20	25
Volumetric joint count Rating (B_s)	>30	30–10	10–3	3–1	1
	5	15	30	45	50
Weathering Rating (W)	Completely	Highly	Moderately	Slightly	Unweathered
	0.6	0.7	0.8	0.9	1.0
Relative ground structure Rating (J_s)	Very favourable	Favourable	Slightly unfavourable	Unfavourable	Very unfavourable
	0.5	0.7	1.0	1.3	1.5

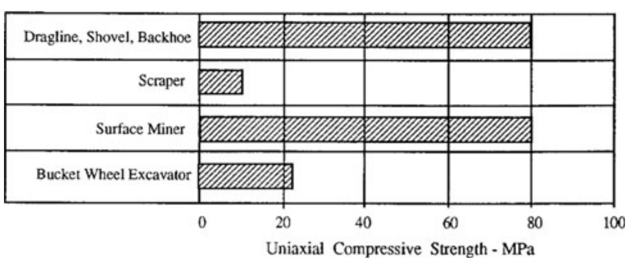

Fig. 6 Application range of equipment based on rock strength (Kolleth 1990)

Table 6 Diggability assessment from laboratory specific energy (Bolukbasi et al. 1991)

Rock class	Laboratory specific energy (MJ/cm^3)	
	Minimum	Maximum
Easy	0.5	1.94
Diggable	1.12	3.72
Hard	1.73	4.81
Marginal	2.64	8.58
Undiggable	>2.64	>8.58

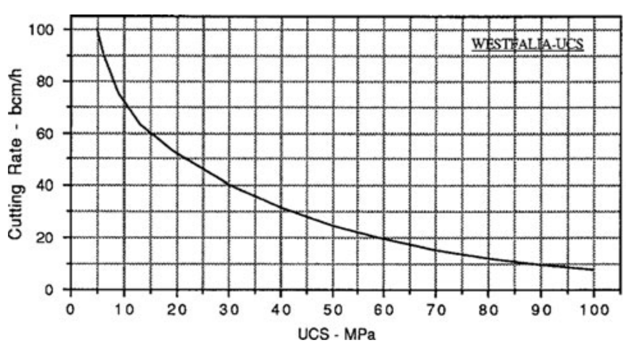

Fig. 7 Change in the cutting rate of road header with UCS (Natau et al. 1991)

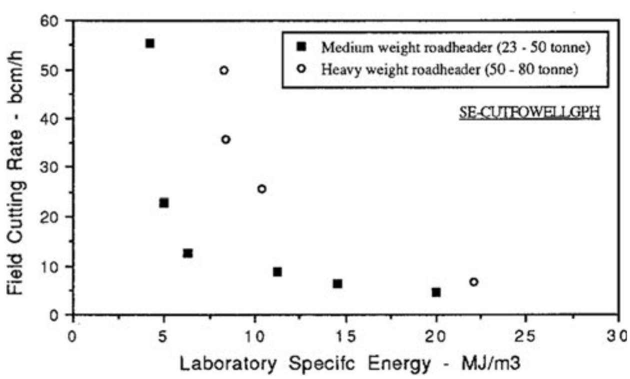

Fig. 8 Cutting rate of road header from specific energy (Fowell and Johnson 1991)

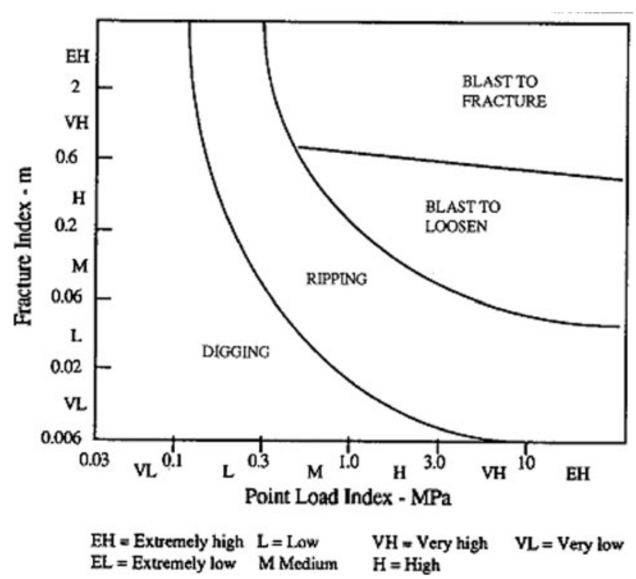

Fig. 9 Proposed zones for digging, ripping and blasting (Franklin et al. 1971)

joint separation. Kirsten formulated an Excavatability Index, a similar system like NGI 'Q' Index, as follows:

$$N = M_s \frac{\mathrm{RQD}}{J_n} J_s \frac{J_r}{J_a} \quad (8)$$

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 7.

Pettifer and Fookes (1994) proposed a classification to assess the rippability of the rockmass. Similar to Franklin et al. in this classification, the point load index and the discontinuity spacing index have also been utilized (Fig. 10).

Table 7 Assessment of rippability based on excavatability index (Kirsten 1982)

Excavatability index	Possibility of ripping
$1 < N < 10$	Easy ripping
$10 < N < 100$	Hard ripping
$100 < N < 1{,}000$	Very hard ripping
$1000 < N < 10{,}000$	Extremely hard ripping/advised blasting
$N > 10{,}000$	Blasting

2.3 Cuttability Indices for Cutting with disc cutter

Graham (1976) 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:

$$P = \frac{3940\,F_c}{\sigma_c} \tag{9}$$

where,

P = penetration rate (mm/rev)

F_c = average cutter force (kN)

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

McFeat-Smith and Tarkoy (1979) correlated the point load index with the advance rate of tunnel-boring machines (TBM) for two types of models, a Robbins 123-133 and a Demag 34-38 TBM models as shown in Fig. 11.

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

$$P = \frac{624\,F_c}{\sigma_t} \tag{10}$$

where,

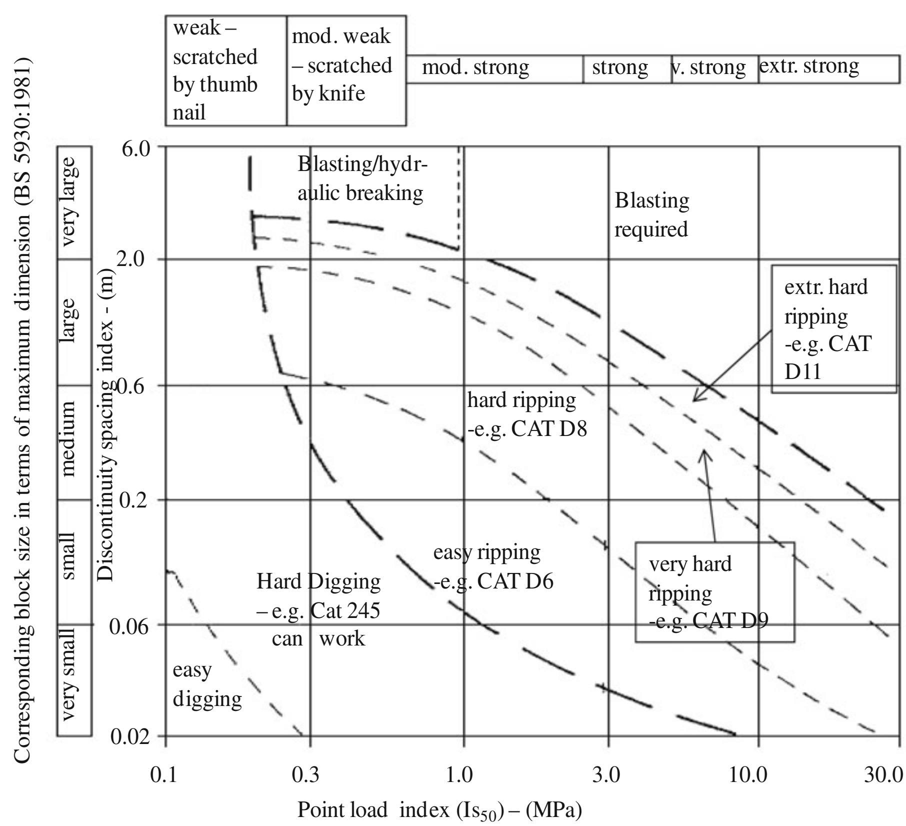

Fig. 10 Rippability assessment by Pettifer and Fookes (1994)

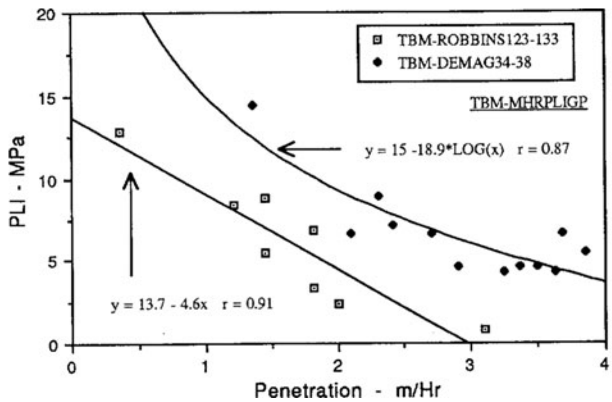

Fig. 11 Relationship between point load index and penetration rate (McFeat-Smith and Tarkoy 1979)

P = penetration rate (mm/rev)
F_c = average cutter force (kN)
σ_t = indirect tensile strength (kN/m^2).

Hughes (1986) established that the advance rate of full-face tunnelling machines with disc cutters is a function of thrust per disc, speed of cutting, average number of discs per kerf, average radius of disc and unconfined compressive strength. The relationship proposed is given as:

$$P = \frac{6 F_t^{1.2} \varpi n}{\sigma_c^{1.2} r^{0.6}} \quad (11)$$

where,
P = penetration rate (m/h)
F_t = thrust per disc periphery (kN)
ω = speed of cutting head (rev/s)
n = average number of disc per kerf
r = average radius of cutter disc (m)
σ_t = unconfined compressive strength (MPa).

Einstein et al. (1979) 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) postulated "there has been no dearth of efforts in adding sophistry to the essential simplistic elegance of classification systems and removing its subjectivity".

3 Cuttability Index 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 that a high-powered machine can cut a relatively stronger rock, the engine power of the cutting machine is also rated in this classification. The ratings of these parameters are tabulated in Table 8.

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

$$\mathrm{CI} = I_s + J_v + A_w + J_s + M \quad (12)$$

The objective of this model is to select a suitable surface miner for an application. So that the requirement of trial run can be avoided. Trial runs may be required for the difficult excavation category. The point load index is used instead of uniaxial compressive strength to reduce the testing difficulties. Abrasivity is an important rock property, which significantly affects the performance and

Table 8 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 (Cerchar)	<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°–90°	54°–72°	36°–54°	18°–36°	0°–18°
Rating (J_s)	3	6	9	12	15
Machine power (kW)	>1,000	800–1,000	600–800	400–600	<400
Rating (M)	4	8	12	16	20

Table 9 Assessment of excavatability of surface miner based on cuttability index

Cuttability index	Possibility of cutting
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

pick cost considerably. Apart from this, an abrasive rock frequently stops the cutting operation for changing of the blunt picks. Volumetric joint count helps to incorporate probability of finding a weakness plane by the surface miner, which eventually decreases the rockmass strength. Similarly, the movement of surface miner with respect to plane of weakness is also important and thus incorporated here. Based on this new cuttability classification, the ease of excavation of rockmass using a surface miner can be classified as given in Table 9.

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 follows:

$$L^{*} = \left(1 - \frac{\mathrm{CI}}{100}\right) k M_{\mathrm{c}} \tag{13}$$

where,

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

M_{c} = Rated capacity of the machine (bcm/h)

CI = cuttability index

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

4 Case Studies

The above model was tested with 20 cases from limestone and coal deposits. Considering the variability to show the

Table 10 Performance analysis of surface miner for three mines

	Coal	Coal Gray Shale patch	Shaly Coal	Limestone		Hard limestone	
				Pit-1	Pit-2	Pit-3 (East)	Pit-3 (West)
Point load index	1.1	2.5	2.2	2.1	2.5	2.7	3.5
I_{s}	10	17	15	20	23	20	25
Volumetric joint count	32	20	33	20	20	10	12
J_{v}	5	8	5	10	10	15	15
Cerchar abrasivity	0.4	1	0.4	1.5	1.5	1.5	1.5
A_{w}	3	6	3	8	8	8	8
Machine power (kW)	448	448	671	448	671	559	783
M_{c}	16	16	10	16	10	16	9
Direction of machine operation with respect to joint plane (deg)	80	80	80	86	86	90	90
J_{s}	3	3	3	3	3	3	3
Cuttability index (CI)	37	51	36	58	55	63	62
Possibility of cutting	Very easy	Easy	Very easy	Easy	Easy	Economic	Easy
Density (t/m^3)	1.6	1.9	1.6	2.2	2.2	2.2	2.2
Cutting condition	Poor	Poor	Poor	Very poor	Very poor	Very poor	Very poor
k	0.6	0.6	0.6	0.5	0.5	0.5	0.5
Rated machine capacity (m^3/h)	400	400	668	400	668	600	845
Expected production achieved (t/h)	243	223	410	184	331	244	353
Actual production achieved (t/h)	225	160	394	143	264	210	317

Table 11 Expected performance of different surface miners

Model	Performance
SM2100	84 m^3/h = 184 t/h
SM2600	126 m^3/h = 277 t/h
SM3500	375 m^3/h = 825 t/h
SM4200	594 m^3/h = 1,306 t/h

range of the model testing three cases are reproduced here–two in limestone and one in coal. The details of the investigations are given in Table 10. The coal mine is situated in eastern India. In this coal mine, the surface miner was used on an experimental basis. The limestone mines are situated in southern India. One of the limestone mines is having hard limestone. Both the limestone mines are sticky and bed moisture is also high.

The expected performance of different surface miners for a particular rock type can also be computed. For example, in a limestone mine (Pit-1) expected production is computed for a few surface miner models and is presented in Table 11.

5 Conclusions

A brief review of the existing cuttability indices has been carried out. A new index has been proposed considering three rock/rockmass parameters, a machine parameter and an application parameter, which are easy to determine. 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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