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Development of a handy methodology for the selection of surface miner in varied rock mass conditions for mass production of coal and limestone

A number of surface miners are being used in Indian mines and construction sites and represent a majority of their global population. The market is growing for these little marvels as several researchers are investigating their application in varied rock mass conditions. Small changes in intact rock and rock mass parameters can adversely affect the performance of mechanical excavators. Therefore, proper planning is required for the selection of surface miner of a desired specification under given geo-mining, intact rock and rock mass conditions. An approach for selection of suitable surface miner has been discussed in this paper. A study has been conducted on the performance of several models of surface miners deployed in Indian coal and limestone mines with special reference to rock properties. A range of rock properties are assessed and analysed with machine performance. Rock cuttability index (RCI) has been developed by taking into consideration all the critical parameters influencing machine performance. A nomogram has been framed for representing the rock cuttability index and production performance estimation. The study involves a comprehensive methodology for the selection of a suitable surface miner, through nomogram, by combining the relevant influencing parameters, namely, intact rock, rock mass, machine design and operating parameters for achieving a desired production.

Keywords: *Surface miner; intact rock; rock mass; rock cuttability index; nomogram*

I. Introduction

A surface miner is one of the mechanical rock excavation machines to extract, crush and load material in one go. Application of surface miner is in a very active phase at different coal, limestone, gypsum, lignite, salt, phosphate, bauxite and iron ore projects around the globe and India, too, is catching up since early 1990s. No requirement for drilling-blasting, selective mining, less dilution, no further crushing and fragmentation etc are the attractive features of the surface miner technology [1]. Presently, surface miners are contributing in a number of projects in various parts of the globe, especially in USA, Russia, Australia and Bosnia apart from India. Out of current global population of nearly 300 surface miners in productive use around the world, some 105 operating machines are in India [2]. Surface miners of various models are being used in India especially in coal and limestone mines. Keeping in view the increased deployment of this machine in India, it is imperative to select an appropriate surface miner after honing in conjunction with different geo-mining conditions. Thus, a study was conducted in coal and limestone mines located in different parts of India as detailed in the paper.

II. Methodology

A. An approach for Surface Miner Selection

The increasing demand of coal and limestone in a short span of time has compelled the mine planners to go for large and mechanized surface mines. Selection of a suitable surface miner is the starting point of any new project as appropriate selection has a major effect on the overall cost and profitability of the project. It requires proper planning based on available predictive models. Performance prediction models, based on a few parameters related to machine specifications, intact and rock mass parameters individually in isolation, are found to have limited applicability. Thus, there is a need for further research in this area so that mine planners may be able to select suitable surface miner to achieve a required production target. The aim of the study, therefore, is to investigate the influence of intact rock, rock mass and machine parameters on the production performance of surface miners of various models in Indian geo-mining conditions. Outline of an approach for appropriate selection of surface miner to achieve production of desired range is shown in Fig.1.

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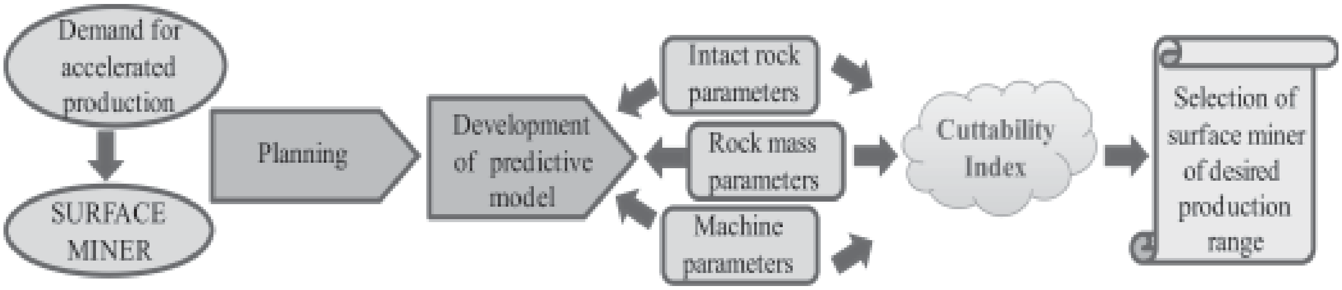

Fig.1 An approach for selection of surface miner

B. Surface Miner Models Deployed in Study Sites

Field investigations were conducted in six mines (three coal mines and three limestone mines), spreading across India, where surface miners are deployed for mineral extraction. The coal mining sites were Sonepur Bazari opencast mine of Eastern Coalfields Limited (ECL), West Bengal, Lingaraj opencast project of Mahanadi Coalfields Limited (MCL) located in Orissa and Gevra opencast project of South Eastern Coalfields Limited (SECL) situated in Chhattisgarh. The study sites of limestone mines located in different parts of India were Dalavoi Works of India Cements Ltd. and Alathiyur Works of Madras Cements Ltd. located in Tamil Nadu and Jadua limestone mine of Sanghi Industries Ltd., Gujarat, where production by surface miners is underway. The location of study sites distributed in different parts of India is shown in Fig. 2 [3]. The data of Talabira coal mine was collected through literature review [4].

Fig.2 Location of study sites in different parts of India

The major rock types excavated were limestone with marl and clay, nummelitic limestone, fossiliferous limestone, clay, coal, carbonaceous shale and coal bands etc. A number of models of surface miners, mainly Wirtgen and L&T make, were deployed in coal and limestone mines as given in Table I. The machine power ranged from 450 to 950 kW.

Table I Models of surface miners studied

	Mine	Surface miner model	Power (kW)	Drum width (m)	Drum radius(m)
1	Sonepur Bazari	2200SM	597	2.2	0.57
2	Gevra opencast project	KSM304	895	3.0	0.675
3	Lingraj opencast project	KSM223	597	2.2	0.57
4	Dalavoi,	2100SM	450	2.0	
	Tamil Nadu	2200SM	597	2.2	0.52
5	Alathiyur,	2100SM	450	2.0	0.52
	Tamil Nadu	2200SM	597	2.2	0.57
		2500SM	783	2.5	0.70
6	Jadua, Gujarat	SF202M	515	2.0	0.52
		KSM304	895	3.0	0.675
7	Talabira coal mine	SM3800	950	3.8	0.70

C. Range of rock, machine design and operating parameters

Intact rock and rock mass properties assume significant importance in cutting performance of surface miner [5-9]. Hence, it is important to identify various influencing geotechnical parameters and their inter relationships for assessing and evaluating production performance of surface miners.

Intact rock and rock mass parameters were analyzed in various coal and limestone mines of India to have a better perception of their influence on the performance of the surface miner. The machine operating parameters, i.e., depth of cut and cutting speed of surface miner were also studied in different mines.

The average, minimum and maximum range of variation with standard deviation (SD) of each parameter is detailed in Table II.

σ_c = uniaxial compressive strength (MPa), σ_t = Brazilian tensile strength (MPa), I_s= point load strength index (MPa), E = Young's modulus (GPa), ν = Poisson's ratio, CAI = Cerchar abrasivity index (mm 10^{-1}), LV_p= laboratory P-wave velocity

TABLE II ROCK PARAMETERS AND MACHINE PERFORMANCE VARIATIONS IN COAL AND LIMESTONE

Parameters		Mean	Minimum	Maximum	SD
Intact rock	σ_c	23.4	12.0	36.0	6.7
	σ_t	3.3	1.0	6.4	1.3
	I_s	1.4	0.2	2.8	0.8
	E	13.7	1.3	35.8	10.1
	v	0.2	0.1	0.4	0.1
	CAI	0.3	0.2	0.7	0.2
	LV_p	2890.0	1217.0	5095.0	1156.8
	SI	5.9	1.0	16.0	5.9
	γ	1.8	1.15	2.53	0.5
Rock mass	RN	26.9	13.0	47.0	9.5
	IV_p	1623.9	371.0	4464.0	1119.4
Machine performance	TPH	516.1	140.0	1180.0	321.8
	DOC	0.18	0.09	0.44	0.08
	CS	11.8	2.5	22.0	5.1
	CA	1.21	0.62	2.32	0.51

(m/s), SI = silica (%), γ = density (t/m^3), RN = Schmidt rebound hardness number, IV_p = *in-situ* P-wave velocity (m/s), TPH = production in tonne per hour, DOC = depth of cut (m), CS = cutting speed (m/min), CA = cutting area (m^2)

The drum cuts the rock in an arc as shown in Fig.3.

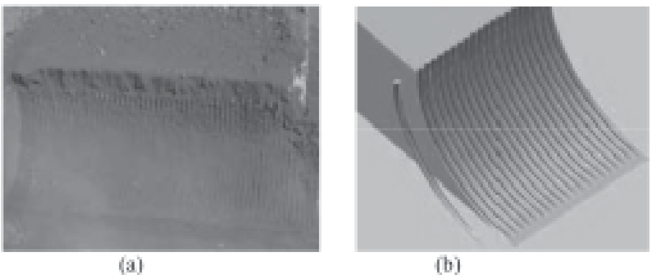

Fig.3 Arc shaped cut rock by the surface miner

Thus, area of the cutting drum in contact with the rock is the product of drum arc length (La) and drum width (W). The arc length in contact with rock is shown in Fig.4 and is expressed as:

$$La = \frac{2\pi R\cos^{-1}\left(\frac{R\text{-}DOC}{R}\right)}{360} \qquad \text{... ... 1}$$

Where,

La = length of arc of drum in contact with rock (m),

R = drum radius (m) and

DOC = depth of cut (m).

The length of arc depends on depth of cut. The equation 1 is based on various drum design specifications available. This relation holds good provided the depth of cut is less than radius of drum.

It is important to know the range in which the maximum occurrence or frequency of each parameter falls because this

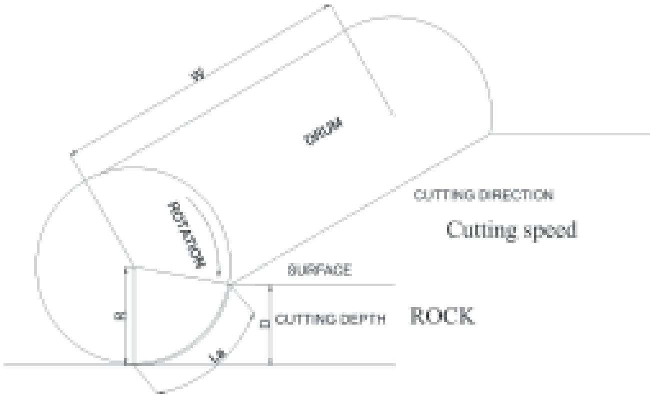

Fig.4 Length of arc of drum in contact with the rock during cutting operation

will help in projecting and guiding the range in which machine is likely to perform. Range and frequency of rock mass and intact rock are given in Tables III and IV respectively.

TABLE III RANGE AND FREQUENCY OF ROCK MASS PROPERTIES IN COAL AND LIMESTONE MINES

RN		IV_p	
Range	F	Range	F
10-15	4	0-500	8
15-20	7	500-1000	7
20-25	6	1000-1500	1
25-30	9	1500-2000	4
30-35	4	2000-2500	10
35-40	4	2500-3000	4
40-45	3	3000-3500	1
45-50	1	3500-4000	1
-	-	4000-4500	1

F = frequency

The compressive strength of rock varied between 12 and 36 MPa, maximum in the range of 15 to 30 MPa. The average Brazilian tensile strength was around one-seventh of average compressive strength. Point load strength index, Young's modulus, Poisson's ratio, Cerchar abrasivity index and laboratory P-wave velocity dominantly ranged in 1-2, 5-10 GPa, 0.2-0.25 and 0.2-0.3, 2000-3000 m/s and 14-16%, respectively. The percentage of silica was above 3 in limestone but it was less in coal. The dominant range of each parameter was highlighted by shading in the respective tables. Density of coal lied below 1.4 t/m^3. Density of limestone was high up to 2.53 t/m^3.The values of average Schmidt rebound hardness number and in-situ P-wave velocity ranged maximum between 15 to 30 and 2000 to 2500 m/s respectively.

The average laboratory P-wave velocity was found to be around 1.7 times higher than the in-situ P-wave velocity. The less value of in-situ P-wave velocity was due to the presence of joints and layers of shale or dirt bands, which was very common in coal mines.

The geological formations especially intercalation of

Table IV Range and frequency of intact rock parameters observed in coal and limestone mines

σ_c		σ_t		I_s		E		i		CAI		LV_p		SI	
Range	F	Range	F	Range	F	Range	F	Range	F	Range	F	Range	F	Range	F
10-15	4	1-2	6	0.5-1.0	2	0-5	2	0.10-0.15	2	0.1-0.2	7	1000-1500	4	0-2	17
15-20	10	2-3	9	1.0-1.5	12	5-10	21	0.15-0.20	6	0.2-0.3	16	1500-2000	4	2-4	5
20-25	9	3-4	16	1.5-2.0	12	10-15	3	0.20-0.25	15	0.3-0.4	4	2000-2500	8	4-8	2
25-30	10	4-5	3	2.0-2.5	3	15-20	3	0.25-0.30	7	0.4-0.5	2	2500-3000	7	8-12	2
30-35	4	5-6	2	2.5-3.0	2	20-25	2	0.30-0.35	7	0.5-0.6	1	3000-3500	3	12-14	4
35-40	1	6-7	2	3.0-3.5	7	25-30	4	0.35-0.40	1	0.6-0.7	5	3500-4000	3	14-16	5
-	-	-	-	-	-	30-35	1	-	-	-	-	4000-4500	5	-	-
-	-	-	-	-	-	35-40	2	-	-	-	-	4500-5500	4	-	-

different layers of rock like marl and limestone lead to variation in-situ P-wave value. Such observations were found in limestone mines.

III. Results and discussion

A. Identification of Critical Parameters

Literature review initially helped in identifying the parameters that have a bearing on the production performance of cutting machine. Artificial Neural Network (ANN) analysis on the data generated from field and laboratory studies helped in identifying the relative importance and sensitivity of different parameters influencing production.

The correlation analysis of each parameter with machine performance further helped in scrutinizing and screening the parameters into critical category. Critical parameters were analysed for development of rock cuttability index.

B. Rock Cuttability Index for Surface Miner

Any technological index reflects the complexity of properties of rocks and is a function not solely of the rock itself but also of the mechanism acting on it [10]. Rock cuttability index assessment may be considered helpful because in this test the interaction of the individual parameters can be imitated for every rock and it is possible to simulate with the performance of the surface miner. It is quite obvious that there must be a relationship between the parameters of machine specifications, operational conditions, intact rock and rock mass parameters and the production. Thus, the cuttability index values provide a better possibility to determine the cutting rate (in tonnes per hour) actually achievable in a given rock.

Cuttability refers to proneness to rock break under standard work conditions, with a certain fixed amount of energy consumption. Several rock parameters contribute to the real cuttability of rock. Sufficient knowledge of the geotechnical behaviour of the rock was obtained by carrying out extensive testing in the laboratory as well as in the field. Rock cuttability depends primarily on intact rock, rock mass and machine parameters. Therefore, rock cuttability index for surface miner was developed considering relevant machine, intact rock and rock mass factors, as discussed below.

a) Machine factor

Engine power capacity, drum specification and operational condition, i.e., cutting area and cutting speed of surface miner are the major influential parameters which play paramount role in the quantitative projection of production apart from intact rock, rock mass parameters. Machine factor (MF) was determined by different approaches, each of which correlated with actual production. The best fit relation of the machine factor was figured out by combining all these parameters, equated as:

$$MF = \frac{EP \times CA \times CS}{1000} \qquad \text{... ... 2}$$

Where,

MF = machine factor,

EP = engine power (kW),

CA = DW×La= cutting area of drum (m^2) and

CS = cutting speed (m/min).

The portion of the drum in contact with rock during the process of cutting is considered as cutting area, which depends on width and radius of the drum and depth of cut.

b) Intact rock factor

Among different intact rock parameters, a combination of Young's modulus, Cerchar abrasivity index and laboratory P-wave velocity showed the best fit relation with production and the same is expressed as:

$$IRF = E \times CAI \times LV_p \qquad \text{... ... 3}$$

Where,

E = Young's modulus (GPa),

CAI = Cerchar abrasivity index,

LV_p = laboratory P-wave velocity (km/s) and

IRF = intact rock factor.

c) Rock mass factor

In-situ P-wave velocity and rebound hardness number were measured at the places where surface miner was deployed in various coal and limestone mines, to evaluate the rock mass strength. These parameters yielded better relation with production and hence considered for determining rock mass factor (RMF). It is an important parameter which represents the in-situ ground condition like joints and rock layers etc. The rock mass factor is expressed as:

$$RMF = IV_p/RN \qquad \text{... ... 4}$$

Where,

RMF = rock mass factor,

IV_p = *in-situ* P-wave velocity (m/s) and

RN = rebound hardness number.

The relation of machine factor, intact rock factor and rock mass factor with production is given in Table V. The actual production showed linear regression with machine factor. Production increased with increase in machine factor. The machine factor ranged maximum up to 40. The intact rock factor showed relation in the power form with production.

TABLE V RELATION OF MACHINE FACTOR, INTACT ROCK FACTOR AND ROCK MASS FACTOR WITH PRODUCTION

	Factor	Equation	Index of determination (R^2)
1	Machine factor	TPH = 31.69MF+146.2	0.97
2	Intact rock factor	$TPH = 1142.IRF^{-0.43}$	0.82
3	Rock mass factor	$TPH = 3577RMF^{-0.58}$	0.78

TPH = production (t/h), MF = machine factor, IRF = intact rock factor, RMF = rock mass factor

The trend of relation depicted that production decreased with increase in intact rock factor. The maximum range of intact rock factor was up to 120. The production was related to rock mass factor in the power form. The production decreased with increase in rock mass factor. The rock mass factor ranged maximum up to 200.

TPH = production (t/h), MF = machine factor, IRF = intact rock factor, RMF = rock mass factor

d) Rock cuttability index for surface miner

Rock cuttability index for surface miner (RCI_{SM}) was considered by taking machine factor, intact rock factor and rock mass factor and is expressed as:

$$RCI_{SM} = 1000\frac{MF}{IRF \times RMF} \qquad \text{... ... 5}$$

Where,

RCI_{SM} = rock cuttability index for surface miner,

MF = machine factor,

IRF = intact rock factor and

RMF = rock mass factor.

The rock cuttability index for surface miner (RCI_{SM}) was closely associated with actual production. The actual production was related to power formed with RCI_{SM} and is expressed as:

$$TPH = 181.5RCI_{SM}^{0.245} \quad (R^2 = 0.85) \qquad \text{... ... 6}$$

The index of determination (R^2) of the relation was 0.85. Production increased with increase in rock cuttability for surface miner.

IV. Development of a nomogram

A nomogram for representing the rock cuttability index was developed, taking the maximum range of machine, intact rock and rock mass factors into consideration. The rock cuttability index for surface miner (RCI_{SM}) was categorized into five divisions based on production, as tabulated in Table VI [11].

TABLE VI ROCK CUTTABILITY INDEX BASED ON PRODUCTION

	Production range (t/h)	Rock cuttability index	Representation
1	900-1200	Excellent	E
2	700-900	Very good	VG
3	500-700	Good	G
4	300-500	Moderate	M
5	<300	Poor	P

The maximum range of machine factor, intact rock factor and rock mass factor was up to 40, 120 and 200, respectively. A rock cuttability index chart was developed by taking the maximum range of machine, intact rock and rock mass factors into account as shown in Fig.5.

The machine factor was divided into three parts (>30, 15-30 and <15) and, therefore, a triangle of three sides was scaled accordingly. Machine factor was taken as the outer most scale because it is the dominant factor with highest weightage among other factors for production. Intact rock factor was divided into five parts along each side of the triangle (0-5, 5-20, 20-50, 50-90 and >90), lying under the category of each range of machine factor. Each division of intact rock factor was further sub-divided into four sectors (0-20, 20-50, 50-100 and >100) by rock mass factor. All the parameters and conditions were covered by making divisions in this fashion.

In a few sectors, combinations like E-VG, VG-G, G-M, M-P were used due to overlapping of production range as shown in Fig.5. The cuttability index for surface miner is directly proportional to machine factor and inversely proportional to intact rock and rock mass factors. If the value of machine factor is high within the scale and values of intact rock factor and rock mass factor are small, the cuttability index and, in turn, production will be higher. The situation will be vice versa under reverse condition. Hence, the exact category of rock cuttability index can be estimated by judging the values of these factors.

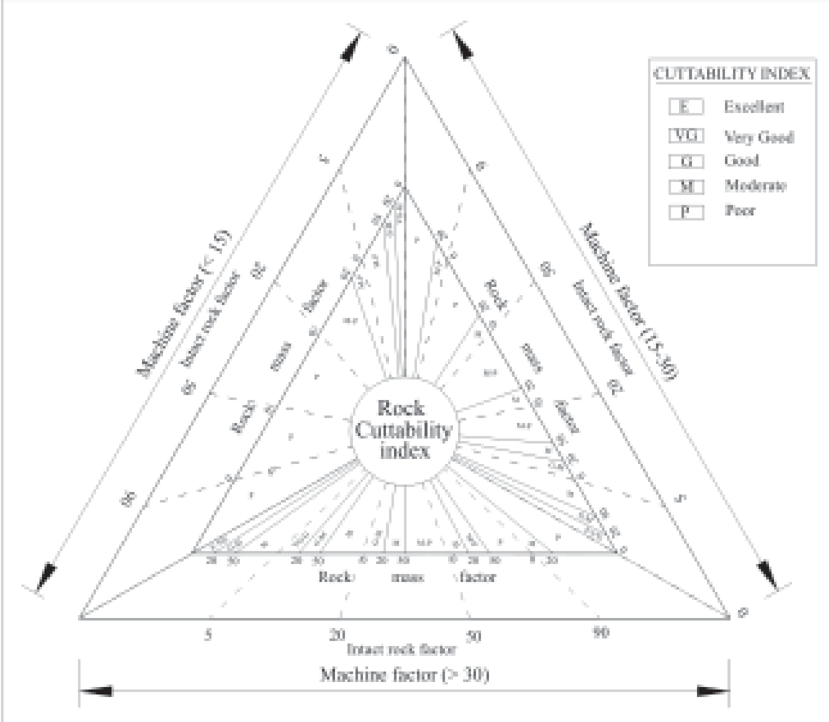

Fig.5 Nomogram for selection of appropriate surface miner.

A. Comprehension of Nomogram and Selection of Surface Miner

Surface miner of suitable specification with special reference to machine power and drum dimension can be selected from this nomogram for achieving desired range of production if the rock properties of the site are determined or known. It is very easy to read the chart. For instance, if the production target is ranged between 700 and 900 tph, i.e., VG range as per Table VI, position of "VG" in the innermost triangle of the nomogram is located. In this case, there are two locations of "VG". The innermost triangle scales the RMF. The value of RMF is calculated from equation 6. The production target can only be achieved if the value of RMF lies below 20. The value of IRF (scaled in the outer triangle), calculated from equation 3, should also be less than 5 to achieve the desired production target. Outmost scale range is for MF. Two sides of the triangle can be opted, i.e., machine factor (>30) and machine factor (15-30) to achieve the target.

If the values of RMF and IRF are close to 20 and 5, respectively, MF of >30 should be opted or if these values are close to 1, MF of (15-30) range should be preferred. Suitable surface miner can be selected based on the specifications of various models available so as to achieve the MF of required range.

V. Conclusion

Performance of surface miner relies on the physico-mechanical properties of intact rock, rock mass, design and operating parameters of surface miner. Therefore, adoption of a selective specification of surface miner presupposes a very thorough knowledge of the correlation between the parameters of the intact rock, rock mass and that of the machine. A rock cuttability index for surface miner was developed considering machine, intact rock and rock mass factors. An easy to use nomogram for selection of surface miner of desired specification was also developed. It is expected that the suggested methodology would be beneficial to mine planners and equipment manufacturers for exercising a rational choice in the selection of surface miner as well as estimation of achievable production for a given rock mass condition. Application of this nomogram in practice can lead to further fine tuning of the same.

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