Critical Evaluation of Industrial Mineral Mining Methods in Sri Lanka

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Abstract
Sri Lanka is rich in industrial minerals, including graphite, apatite, ilmenite, rutile, quartz, feldspar, kaolin, apatite, garnet sand, mica, calcite, and dolomite. Even though lots of mining methods are used to extract such minerals, only limited studies have been carried out in Sri Lanka to evaluate mining methods by means of main mining principles, such as safety, economy, and efficiency. This study focuses on the Bogala graphite mine, a narrow vein medium depth underground mine, and Aruwakkalu limestone open pit mine. To evaluate the overhand cut and fill mining method in Bogala mine, Equivalent Linear Overbreak or Slough (ELOS), which is a useful measurement for quantifying the unplanned dilution in narrow vein mining, is used. The favourability of the underground mining method is evaluated for a particular mine site using Key Deposit Indicators (KDIs), and it provides the best suited underground mine based on characteristics of the ore body. The fracture system presence in the Bogala mine requires a good support system to ensure the safety of underground workers. The efficiency of the loading and hauling equipment in the Aruwakkalu mine site is evaluated by Match Factor (MF).

Keywords: ELOS, KDI, Limestone, Match factor, Narrow vein, RMR

1. Introduction

Industrial minerals include all those materials that man takes out of the earth's crust except for fuels, metallic ores, water, and gemstones [1]. Consideration of basic mining principles (safety, efficiency, and economy) is essential in the evaluation of mining methods.

1.1 Sri Lankan Mining Industry

About 2.3% of the Gross Domestic Product (GDP) by industrial origin is due to the mining and quarrying industry as per the Central Bank Annual report 2019 [2]. Mainly graphite, ilmenite, rutile, zircon, kaolin, ball clay, feldspar, vein quartz, silica, apatite, calcite, dolomite, mica and are mined as industrial minerals using modernized or traditional mining methods in Sri Lanka.

1.2 Mining Method in Bogala Graphite Mine

In Bogala Mine, the overhand cut and fill mining method is practised with the deepest operation level of 503 m. Prior to the mining, 1.1 m * 60 m * 60 m (W*L*H) block is defined, including two main levels and two winzes. Then 1.1 m * 2.0 m (W*H) area is excavated along the vein.

1.3 Mining Method in Aruwakkalu Limestone Mine

Aruwakkalu Limestone Mine extends its land coverage up to an area of 4454 acres, and more than 450 acres has been mined out already, which is about 10-15% of the demarcated land area for the mining. The open-pit mining method is practised at this mine. The stripping ratio of the mine is 1.6. Several nearly vertical benches are developed on the red soil layer, with approximately 2.1 m bench height and 4 m bench width. The specific charge value stipulated by the Geological Survey and Mines Bureau (GSMB) is 0.15 kg/mt for Aruwakkalu Mine [3].

1.4 Evaluation of Bogala Mine

The average vein thickness of graphite in Bogala Mine is in the range of 20 to 40 cm. It is called a narrow vein graphite mineralization. However, currently, Sri Lanka is the only country mining vein-type graphite for the commercial purpose [4]. During narrow vein mining, dilution can extremely be increased. ELOS index measures the unplanned dilution in underground mining. The main advantage of the ELOS index is that it doesn't depend on mining width. ELOS is a useful measurement for quantifying the dilution in narrow vein mining because narrow vein dilution is highly sensitive to the stoping width.

Bieniawski (1973) published an RMR classification system to classify the rock mass and to decide the suitable support system for underground excavations. Due to the fracture system present in the Bogala host rock, a heavy support system is used. This consists of steel as well as timber. Therefore, RMR value for host rock and consumption of support material per block of Bogala Mine was estimated in this study. Generally, there are three kinds of supporting systems practised in Bogala Mine as cap support, set support and rock bolting.

Open stope mining method was replaced by overhand cut and mining method in Bogala Mine after 165 m level [5]. To adopt most favourable mining method based on spatial characteristics of ore body, Key Deposit Indicators (KDIs) are used. Ore strength, host rock strength, deposit shape, deposit dip, deposit size, ore grade, ore uniformity and deposit depth are the main parameters in the determination of KDIs.

1.5 Evaluation of Aruwakkalu Mine

The largest material handling process in the Sri Lankan mining industry is practised at Aruwakkalu Limestone Mine. A Caterpillar 374F L type excavator and three HD 465-7R type dump trucks are used in the Aruwakkalu quarry for material handling with 6 to 7 tons and 55 tons of capacity, respectively.

Evaluation of cycle time of loading and hauling process is measured as per the optimum requirement of machinery to increase the process efficiency with minimum cost. Match Factor (MF) is measured suitable fleet composition number between loading and hauling equipment. MF=1 indicates 100% efficiency of operation between loading and hauling equipment.

2. Methodology

2.1 Data Collection

Mining engineers were interviewed during the field visit to obtain necessary data related to mining operations on sites. In Bogala Graphite Mine, a survey was conducted using Total Station (Sokkia iM-52) to determine the unplanned dilution at 275 FM level in Bogala Mine. A field survey was conducted using a stopwatch to calculate the cycle time of dumpers and the excavator at Aruwakkalu Limestone Mine.

2.2 Analysis of Data Evaluation of Bogala support system

A detailed fracture survey has been conducted on the main crosscut at 503 m level in "Kumbuk Vein" to identify the weathering condition, continuity and spacing of discontinuities, roughness of the surface, mineral intrusion, and groundwater condition within fractures. Occasionally, Quartz, Pyrite and Mica can be observed within fractures as mineral intrusions. According to the survey observations, fractures are continuous, and most of them have rough surfaces. On average, 1,000,000 m^3 of water is pumped out from Bogala Mine every day.

According to the observation rate for relevant parameters in the RMR classification system are included in Table 1. Consumption of support material used in Bogala Mine for cap supports and rock bolts and cost of them are included in Tables 2, 3 and 4, respectively.

Table 1: Rate for parameters in RMR for Bogala Mine.

Parameter	Observation	Rate
UCS	137.9 –206.8 MPa	12
RQD	99%	20
Spacing of discontinuities	2.4 m	20
Condition of discontinuities	Slightly rough surface, Separation < 1 mm, Highly weathered wall rock	20
Groundwater	Infiltering moderate pressure	4
Orientation of discontinuities	Favourable	-2

Material consumption for a 60 m * 60 m block

Space between two successive anchors (Y) = 4 ft

Overlap length of two successive timber planks (X) = 2 ft

Overall Length of one support cycle (X+Y) = 6 ft

No. of support cycle using timber caps per block = 1450

No. of support cycle using SH rails per block = 50

Table 2: Consumption of material for cap support per 60 m * 60 m block.

(D-Diameter, L-Length, T-Thickness, W-Width)

Support Type	Dim. of Unit Item	No of Items per cycle	Total Qua. Per cycle	Total Quantity per block
Timber cap	D=25 mm L=1.1 m	1	1.1 m	1595 m
Timber plank	T=2" W=6" L=8'	7	56'	84000'
SH rail	L=1.1 m	1	1.1 m	55 m
Anchor	D=30 mm L=4′	2	8′	12000′
Anchor support	D=30 mm L=1′	2	2′	3 000′

Table 3: Consumption of material for rock bolts per 60 m * 60 m block.

Support Type	Dim. of Unit Item	No of Items per block	Total Quantity per block
Stem of Rock bolt (3 ft)	D=25 mm L=3′	30	90 ft
Stem of Rock bolt (5 ft)	D=25 mm L=5'	10	50 ft
Nut	D=25 mm	40	40
Wedge	L=2″ W=1″ T=3 mm	40	40 * (2″X1)=80 $inch^2$
Plate washer	L=5″ W=5″ T=3 mm	40	40 * (5″X5″) =1000 $inch^2$

Labour cost estimation for a 60 m * 60 m block

Duration of a working shift	5 hrs
Total hours required to complete a support cycle	2 shifts
Total number of hours required to fix a support	10 hrs
Number of workers required to fix the support system	3
Average monthly salary per labour	Rs. 80,000
Average labour salary per hour (80 000/200)	Rs. 400
Total labour cost per block (400*10*3*1500)	**Rs. 18,000,000.00**

Cost of material for support system per 60 m * 60 m block

Table 4: Cost evaluation of material for cap supporting and rock bolting per block.

Type of support	**Req. quantity**	**Unit Cost (Rs)**	**Total Cost (Rs)**
Logs	1595 m	31.63/ dc³	2,475,196.00
Timber plank	84,000 ft	350/ft	29,400,000.00
SH rails	183.15 ft	1 045/ft	191,392.00
Anchor	12,000 ft	280/ft	3,360,000.00
Anchor support	3,000 ft	280/ft	840,000.00
Stem of rock bolts (3 ft)	90 ft	208/ft	18,720.00
Stem of rock bolt (5 ft)	50 ft	208/ft	10,400.00
Nut of rock bolt	40	80	3,200.00
Wedge of rock bolt	80 inch²	2.50/ inch²	200.00
Plate washer of rock bolt	1000 inch²	2.50/ inch²	2,500.00
Total (Rs)		**36,301,608.00**	

Evaluation of unplanned dilution in Bogala Mine based on ELOS index

Based on data collected from the survey, an isometric 3D view was prepared using AutoCAD software to determine excavated rock volume.

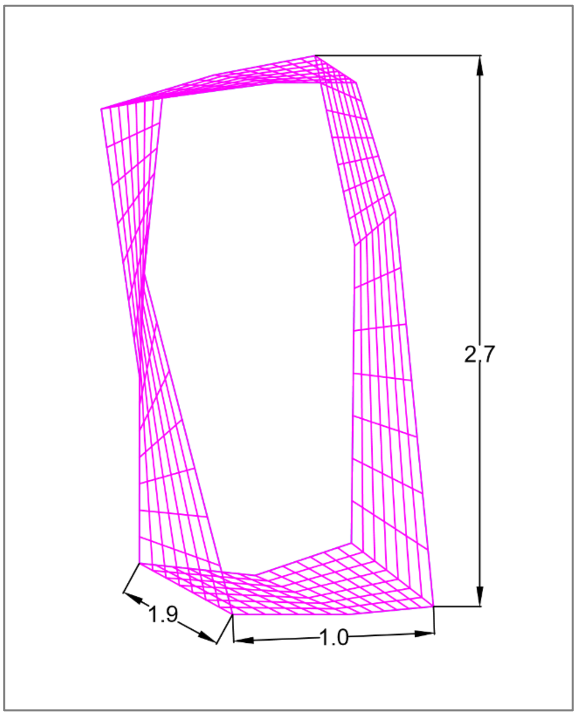

Figure 1: Isometric view at location no:1 at 275 FM level (not to scale).

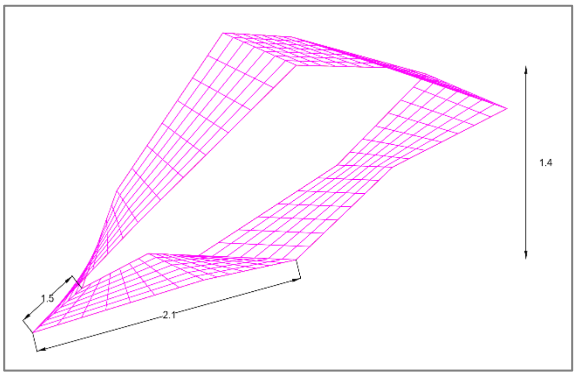

Figure 2: Isometric view at location no: 2 at 275 FM level (not to scale).

Table 5: Calculation of ELOS index for 275 FM level of Bogala Mine.

Location	Total In-situ Blasted Volume[m^3]	Expected Volume[m^3] (H*W*D)	Overbreak Volume [m^3]	Expected Stop Height[m]	Expected Strike Length[m]	ELOS Index [m]
1	3.845	2*1.1*1.2=2.64	1.205	2.0	1.2	0.5021
2	2.935	2*1.1*1.2=2.64	0.295	2.0	1.2	0.1229

The solid rock volume expected to be excavated in the blasting was estimated based on dimensions, and ultimately differences between the actual and expected rock volume (overbreak) were calculated. Then ELOS was determined using equation (1).

ELOS=Volume of overbreak or slough/ stope height*wall strike length (1)

Evaluation of performance in material handling at Aruwakkalu Limestone Mine

Cycle time of dumper is the summation of loading time, hauling time, dumping time, returning time, spotting time and waiting time. Spotting time is defined as the positioning time of the hauler at the loading or dumping point. Excavator cycle is given by summing loading time, drawing time, swing time with load, swing time without load and waiting time.

Table 6: Performance of dumpers.

Machine	Avg. cycle time (min:sec)	Avg. load per cycle(t)	Production Capacity (t/h)
DT 551	14:34	51.55	212.33
DT 552	15:43	53.54	204.43
Dt 553	16:50	53.89	192.08
Average	**15:42**	**52.99**	**202.48**

Avg. cycle time of excavator = 49.24 sec

MF is measured as per equation (2).

$$MF = \frac{NF*CTL*NH}{CTH*NL} \qquad (2)$$

Where:

MF = Match Factor
NF = no. of filling for each hauling equipment
CTL = cycle time of loader (sec)
NH = no. hauling equipment
CTH = cycle time of hauler (sec)
NL = no. of loading equipment

MF for Aruwakkalu Limestone Mine = 1.0977

The hauling process at the Aruwakkalu quarry takes 9.5 hours per day in the week. However, material hauling activities are completely stopped in November and December month due to heavy rainfall. Therefore, the contribution of the material handling process to achieve the annual production is targeted as follows:

Total no of working days per year	300 days
No of working hrs/day	9.5 hrs
No of dumpers	3
Avg Cycle Time of dumper	942 sec
Avg load per cycle	52.99 t
No of cycles per day by a single dump truck (9.5*3600/942)	36
Achievable production target per day (36*3*52.99)	5722.92 t
Achievable production target per year (5722.92*300)	1,716,876 t

3. Results

RMR value is calculated by summing all RMR parameters as follows:

RMR for Bogala Mine = 12+20+20+20+4-2
= 74

The total cost for support material (cap support and rock bolting) and labour per

60 m * 60 m block are LKR 36,301,608.00 and LKR 18,000,000.00, respectively.

The average ELOS for Bogala Mine is 0.31 m.

Based on field survey data and available literature, KDI is determined as follow:

Table 7: Resulted KDIs for Bogala Mine.

Key Deposit Indicator	KDI Value for Bogala Mine
Host Rock Strength	3
Deposit shape	4
Deposit dip	4
Deposit Size	1
Ore Grade	4
Ore Uniformity	2
Deposit Depth	3

At Aruwakkalu Limestone Mine, limestone loading and hauling equipment are resulted in Match Factor as 1.098. Based on existing efficiency and recorded cycle times, Aruwakkalu quarry can achieve 1.72 Mn of tons production target per year in term of loading and hauling process.

4. Discussion

Total ratings for rock mass classes published by Bieniawski (1973) was used to evaluate overall condition of host rock in Bogala Mine as follow:

Table 8: Rock classes based on RMR.

Ratings	100–91	90–71	70–51	50–25	<25
Class No.	I	II	III	IV	V
Description	Very good	Good	Fair	Poor	Very poor

According to the result obtained from RMR calculation, rock mass at Bogala Graphite Mine is classified as good rock (class no: 2).

ELOS index less than 0.5 m is considered blast damage only, ELOS index between 0.5 and 1.0 m is minor sloughing, 1.0 to 2.0 m is moderate sloughing and greater than 2.0 m is severe sloughing or possible wall collapse [6]. Average ELOS index for Bogala Mine is 0.31 m. It belongs to blast damage only range which means very low level of unplanned dilution is occurred during the blasting in Bogala Graphite Mine.

According to Table 9, most of the indicators for Bogala Graphite Mine are similar to the favourable KDI of the cut and fill mining method.

Table 9: Favourable KDI for overhand cut and fill mining method.

Key Deposit Indicator	Favourable Condition	KDI Value
Ore strength	Moderate to strong	2,3
Host rock strength	Weak to fairly weak	1, 2
Deposit shape	Any shape	1, 2, 3, 4
Deposit dip	5^0 to 45^0	2, 3
Deposit size/thickness	Small to medium	1, 2
Ore grade	Fairly high	3, 4
Uniformity	Variable or moderate	1, 2
Deposit depth	Moderate to deep	2, 3, 4

Slight differences of Bogala Mine with respect to the favourable condition of cut and fill mining method are host rock strength and deposit dip. The actual strength of the host rock is higher than the expected value. Table 9 indicates that cut and fill mining method is best for weak to fairly weak host rocks. According to the values of Bogala Mine, its host rock strength is high. However, fractures existing within the rock mass decreases the overall strength of the host rock. Although KDI of deposit dip is considered as 4, favourable condition for cut and fill mining method is 2 or 3. It means the dip of the deposit should be between 5° and 45°. However, all graphite veins in Bogala Mine are approximately within 65° to 90° range.

If MF = 1, it indicates 100% efficiency operation between loading and hauling equipment. While, If MF < 1, this indicates hauling equipment works at 100% effective and loading equipment allocates more time for waiting. If MF > 1, this indicates that loading equipment works effectively but waiting time is generated by hauling equipment [7]. MF for Aruwakkalu Mine was 1.098, it is nearly equal to one. So, loading and hauling equipment at Aruwakkalu Limestone Mine works nearly 100% efficiently and at optimum performance under the current conditions.

Further, the annual production target of the Aruwakkalu Limestone Mine is approximately 1.3 million metric tons [8]. According to the current material handling condition, it can achieve a 1.72 million metric tons production target per annum.

5. Conclusions

In Bogala graphite mine, significantly higher cost is incurred for supporting to meet the safety requirement of underground workers. However, economically it is more prefer replacing of existing support materials with a material that ensures the safety requirements with a minimum cost.

According to resulted ELOS index for Bogala Mine, unplanned dilution is maintained at a lower level so that there is no any significant overbreak in the blasting. According to the KDIs overhand Cut & Fill Mining Method is the most favourable mining method for Bogala Mine. According to MF, a highly efficient material handling process exists at Aruwakkalu Mine. Under the current efficiency in the material handling process, Aruwakkalu Mine can achieve a higher production capacity than the expected value.

Acknowledgement

We would like to acknowledge and extend our heartfelt gratitude to our supervisors Eng. P. V. A. Hemalal (Senior Lecturer), Eng. M.M.L. Lasantha (Lecturer), Prof. P. G. R. Dharmarathna (Senior Professor), Dr. S. P. Chaminda (Senior Lecturer) and Dr. C. L. Jayawardena (Senior Lecturer) of the Department of Earth Resources Engineering, University of Moratuwa, Sri Lanka for the excellent assistance and the guidance that contributed to success our final outcomes.

Our special appreciation goes to the management of Bogala Graphite Lanka PLC and Siam City Cement Lanka Ltd for the opportunity given to us to collect the set of useful field data for this research project.

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