Evaluation of Overhand Cut and Fill Mining Method used in Bogala Graphite Mines, Sri Lanka

P G R Dharmaratne, P V A Hemalal and M C Hettiwatte

Abstract

This paper includes the study of the mining method adopted at Bogala Graphite Mines and its suitability compared with other mining methods used in the mining industry. This major graphite occurrence discovered more than hundred years back is mined to extract high-purity vein graphite which is highly valued the world over. In Sri Lanka, graphite mineralizations occur in the form of rich veins with steep dips in the South Western sector of the island, the vast area of land which has been famous for graphite mining with thousands of pits in operation during the boom times of the first and second world wars. Where an outcrop was encountered, a pit had been sunk and the steeply dipping vein had been followed to the depths. At Bogala mines, the adoption of the Overhand Cut-and-Fill mining method is influenced by the steeply dipping vein environment with rock intercalations and high water inflows with less competent country rock. Although cut–and–fill mining has been traditionally successful ensuring high recovery and safety, only limited studies (as shown by Hemalal [1]) have been carried out with an engineering input to evaluate this method. With the use of literature and site visits to Bogala mines, the mining method used at Bogala, the underground environment and the other mining methods used in the mining industry have been studied. In evaluating the most suitable mining method, workability, safety, ore dilution and recovery factors of different mining methods were considered and most suitable method for Bogala was evaluated.

1. Introduction[1]

1.1 Mining Methods- General

Mining is carried out by open-casting and the underground mining, as demonstrated in [2];

- Open casting/surface mining

In surface mining, the operations take place on or closer to the earth's surface. With the use of heavy equipment, overburden is removed and the ore is extracted directly. After recovering the valuable minerals, the barren rock is stored back in restoring the land. Different types of surface mining in use are open casting/quarrying, mountaintop removal, placer mining, dredging, hydraulic and strip mining.

- Underground Mining

This is the removal of valuable minerals from the earth by taking both people and equipment into depths from the earth's surface.

The basis of classification of underground mining methods is ground control. In this way underground mining methods are classified into three areas;

1. Unsupported openings
2. Supported openings
3. Caving methods

The main methods used in underground mining are drift mining, slope mining, shaft mining, borehole process and Hard rock mining.

Hard rock mining is done by creating underground rooms supported by surrounding rocks and artificial supports. Stope and pillar, room and pillar, long hole stoping, cut and fill, benching, vertical crater retreat, block caving and sub-level caving are some of the hard rock mining methods used around the world.

1.2 Mining Method in Bogala

The underground graphite mine located at Bogala is operated by Bogala Graphite Lanka PLC. Mining in this area started more than hundred years ago and still delivers high-purity vein graphite to the world market. At Bogala underground mines, an earlier mining method, a form of open-stoping has been replaced by the overhand cut-and-fill method which has ensured better ground control and safety beyond the depth of 165m below pit-head level.

The Bogala Deposit presents itself in the form of three main veins namely, Na, Mee and Kumbuk which are accessed by vertical shafts, Alfred Shaft continuing down to 132m depth and by Gabriel Shaft (Earlier called the 5th pit), another vertical access to greater depths (Figure 1).

From the shafts horizontal cross-cuts are excavated at approximately 60m intervals linking the shaft to the steeply dipping graphite veins through the host rock. In a further development, horizontal drifts (drives) are excavated along the vein from the cross-cuts. Those adjacent parallel drifts are connected by winzes (openings along the dip of the vein) at 40 to 50m intervals creating 30m*45m graphite blocks in the vein. In the application of the overhand cut-and fill method, ore extraction takes place from bottom upwards while the intact vein is hanging over the stope and the lower void is filled with rock debris as the mining of the block progresses upwards (Figure 2).

The average vein thickness in Bogala mines is about 20 to 40cm. But, in the mining process, a width of about 1.3m to a height of 1.8m is mined out to give enough working space for the mining operations (Figure 3). From the mine, only graphite is hoisted and the blasted rock

[1] PGR Dharmaratne, PVA Hemalal and MC Hettiwatte are with the Department of Earth Resources Eng., Univ. Moratuwa, Sri Lanka. (e-mail: dharme27@yahoo.com; hpanagoda54@gmail.com; manilchathuranga@gmail.com)

material is used for the filling process of the lower level which reduces the cost of hoisting and improves the level of safety by back filling, as shown by Welideniya and Ekanayake [3].

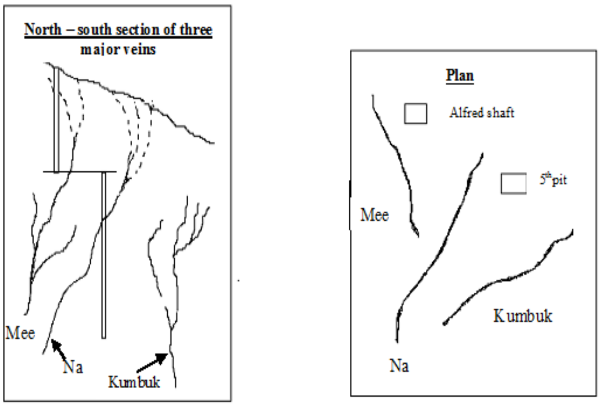

Figure 1: North South and Plan sections of the major veins (Not to scale).

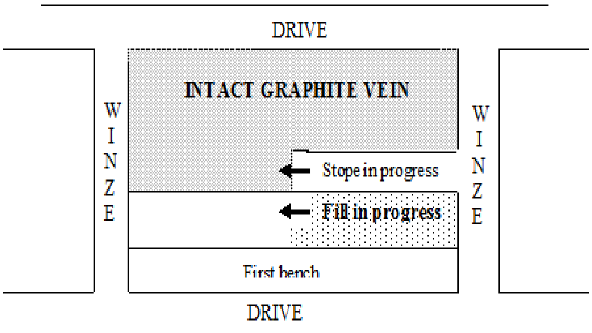

Figure 2: Mining block-side view. This is how a mining block is planned in Bogala mines.

In stoping, the explosives are used to break the rocky part of the profile while the graphite vein is not charged. With the blasting of the profile in this manner, broken rock gets mixed with graphite giving rise to dilution reducing recovery.

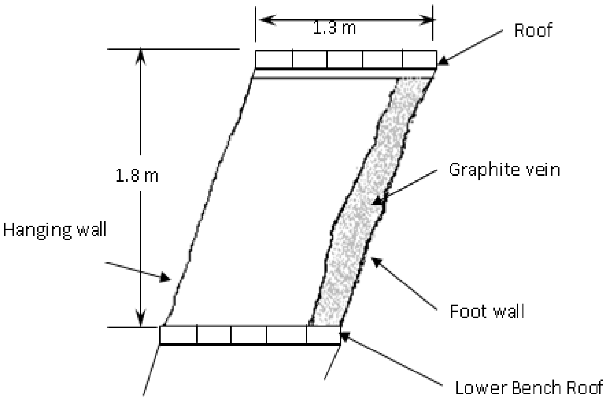

Figure 3: Stope Profile. Out of the profile only about 30% is graphite and the rest is rock.

In Bogala, due to a high number of fractures being located within the mining area, a heavy supporting system consisting of steel as well as timber are used. In a stope, the roof of one level will be the working floor of the level above and good supports are needed (Figure 4). So, for permanent roof fixing, steel supports are used in main drifts and sub-level drifts while in all the other levels, temporary timber supports are used. These fixings act as supports exerting pressure to counteract the stresses from hanging and foot walls.

Figure 4: Roof fixing in Bogala. This was taken during a field visit to Bogala at main cross cut in 503m level.

In some areas where it is hard to contain the fractures, one or combinations of the following support systems are used. Side wall fixing (Figure 5) is carried out with rock bolting, shot-crete in conjunction with wire mesh.

Figure 5: Side wall fixing in Bogala. This was taken at Na veins 2nd working bench in 260m level.

1.3 Graphite Mining Methods

Commercialized graphite mineralizations are found in countries like In Norway, China, India, Canada and England. But most often, graphite is mined through surface mining methods like open pit, mountain top removal and strip mining due to mineralization being very much closer to the earth's surface and also occuring as pockets or horizontal layers.

There are vein type graphite mineralizations in Borrowdale, Cumberland in Great Britain and locations in USA like Dillon Montana and in northwestern New Jersey. But currently-Sri Lanka is the only country mining vein type graphite for commercial use, as demonstrated in [4].

In Sri Lanka, currently there are two other graphite mines operated at Kahatagaha and Ragedara, which are operated respectively by Kahatagaha Graphite Lanka Ltd and Sakura Graphite (PVT) Ltd.

- In Kahatagaha, due to high strength of the rock and less fracture propagation, open stope mining method is used with a minimum number of supports.

- In Ragedara, they also use an open stope mining method with almost no supports due to high rock strength and less fracture propagation (Figure 6).

In Ragedara, after the mining of the 1st bench a slice of about 1m height over the bench is left intact. The second bench is taken keeping this intact slice as the floor. On returning horizontally towards the original position, this slice is mined out. After mining in a similar manner for three levels a 1m thick bench is kept in between without mining to support the walls. The method is called 'Three bench slicing method'.

Figure 6: Open stope mining method at Regedara. Unsupported working stope roof due to rock strength.

1.4 Factors influenced in choosing a mining method

The three basic principles are safety, efficiency (maximum extraction) and economy (lowest cost/ maximum profit). The second and third are closely related and in some cases can be conflicting.

There are several factors which affect the choosing of a mining method, as shown by Dharmaratne [5];

- Spatial characteristics of the ore body:
  size, shape (width/ thickness, vertical extent, regularity), dip, strike, pitch and depth are related to the ore body.
- Physical, chemical and mechanical properties of the ore and the country rock:
  ore and wall rock strength (compressive, tensile and shear), planes of weakness (joints, bedding planes, shear, faults), possibility of degradation, oxidation and mineralogy.
- Ground water and hydro-geological conditions
- Economic factors:
  such as, grade of ore, value of mineral and distribution of values.
- Comparative mining and processing costs:
  cost of labour and materials, desired production rate and geographical considerations (availability of labor and material, infrastructure-essential service, housing, etc...)
- Environmental factors:
  such as, geographical consideration, prevention of air/ water pollution, preservation of the surface and influence of depth (pressure and rock strength)

The choices available when considering the factors are numerous and they range from each end of the spectrum.

2. Methodology

When choosing a mining method, it is important to evaluate the above mentioned factors to the maximum possible extent. They may conflict with one another and it is essential to strike a balance between all the factors. Especially the balance of three the basic principle of safety, efficiency and economy is essential when mining.

2.1 Spatial characteristics of the ore body

In Bogala, the three main veins have been named as Na, Mee and Kumbuk, the three types of traditional timber used as supports. Mee vein has been already mined out and the Mee fracture has merged with Na vein around 344m level. Also close to the Kumbuk Vein, another prospective vein called a Kumbuk split bears hope around 293m level. Unlike at shallow depths, this split vein is the most productive vein out of the production veins in operation. The Spatial Characteristics dip and strike of the Kumbuk vein is 75^0-80^0 and 210^0, and that of Na vein it is 65^0 and 330^0. The average vein thickness in Bogala graphite veins are about 20 to 40cm. According to Bieniewski classification (Table 1 and 2), as shown by Dharmaratne [5], Graphite veins in Bogala can be classified as very thin/ narrow steep dipping ore bodies.

Table 1: Classification of veins according to dip angle. (After Bieniewski)

Angle of Dip	Classification
0^0	Horizontal
0^0-3^0	Conventionally horizontal
3^0-30^0	Gently sloping
30^0-45^0	Inclined
45^0-90^0	Steep ore bodies

Table 2: Classification of ore bodies by their thickness. (After Bieniewski)

Thickness (m)	Classification
0-0.7	Very thin/ Narrow
0.7-2	Thin
2-5	Medium-Thick
5-15/20	Thick
15/20 over	Very Thick/ Wide

The maximum depth of the shaft at Bogala mines is about 560m and the deepest mining level is 503m. According to the explorations carried out it is estimated that the veins progress beyond 600m.

Although the average vein thickness in Bogala is about 20 to 40cm, the irregular nature and behavior of the graphite veins are such that at some places it totally pinches off while in some places parts of the veins present themselves as bulges. Pockets of graphite mineralization can also be encountered in some areas underground.

2.2 Physical, chemical and mechanical properties of the ore and the country rock

The surrounding host rock in Bogala Underground is mainly metamorphic garnet biotite gneiss. According to the Bieniewski classification (Table 3), the metamorphic rocks are strong and they have compressive strengths of 137.9-206.8MPa, as demonstrated in Dharmaratne [5].

Table 3: Rocks classified by strengths and their origin. (After Bieniewski)

Class	Compressive Strength (MPa)	Origin
Weak	Less than 41.3	Coal, Weathered rock, Alluvium
Moderate	41.3-137.9	Shale, Sandstone, Limestone, Schist, Evaporates
Strong	137.9-206.8	Metamorphic, Igneous, Marble, Salt
Very Strong	More than 206.8	Quartzite, Basalt

Point Load tests were carried out with rock samples taken from Bogala Underground. Non-Standard samples were used from different locations of the mine and the point load test values were determined using ISRM graphical method, as demonstrated in [6] (Figure 7).

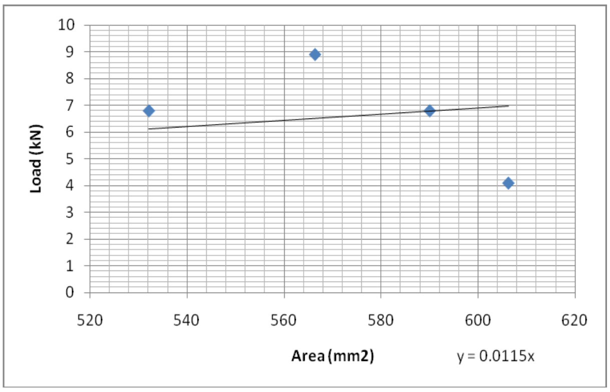

Figure 7: Data of Na Cross-cut in 503 level. Using the straight line the point load for 500 m^2 was found.

Using the graphs, the average point load value was determined as 11.5 MPa, which according to Deere classification is of very high strength (Table 4), as shown by Palmstrong [7].

Table 4: Classification of rocks by Point load strength. (After Deere-1966)

Class	Point Load Value (MPa)
Very High Strength	More than 10
High	5-10
Medium	2.5-5
Low	1.25-2.5
Very Low	Less than 1.25

From Brooks equation (1985) (Eq. 1), as shown by Palmstrong [7], the compressive strength was calculated as 143.75 MPa.

$$\sigma_c = 12.5T^*_{500} \text{ .... Eq. 1}$$

According to the ISRM classification in 1978, the country rock is of very high strength (Table 5), as shown by Palmstrong [7].

Table 5: Classification of rocks by compressive strength. (ISRM-1978)

Class	Compressive Strength Value (MPa)
Soil	Less than 0.25
Extremely Low Strength	0.25-1
Very Low Strength	1-5
Low Strength	5-25
Medium Strength	25-50
High Strength	50-100
Very high Strength	100-250
Extremely High Strength	More than 250

Even though the country rock in Bogala is of very high strength, the mine is located at a fracture zone which reduces its strength. A survey of the fracture system conducted on the main cross-cut at 503m level in Kumbuk vein showed that there are a number of continuous fracture formations in the mining area. Some are tight, but some are open with mineral intrusions such as Quartz, Mica and pyrite (Table 6). The data was collected and tabulated in accordance with the Geomechanics classification of Joint Rock Masses by Bieniewski, as shown by Dharmaratne [5].

Table 6: Fracture survey data from in-situ analysis in main cross-cut at 503m level Kumbuk vein.

Distance from Shaft (m)	Dip/ Dip Direction	Condition	Water and Weathering Conditions
6	23/180	Non-continuous Very tight joints Rough surface No intrusions	Dry unweathered
6.9	13/50	Non-continuous Very tight joints Rough surface No intrusions	Dry unweathered
7	40/210	Continuous Moderately open joints Rough surface No intrusions	Dry slightly weathered
8.5	3/70	Continuous Very tight joints Rough surface 3mm Intrusions (flaky Mica)	Dry slightly weathered
10.8	60/170	Continuous Tight joints (1mm) Rough surface 2cm Intrusions (Copper Pyrite)	Dry slightly weathered
11.3	16/80	Continuous Very tight joints Rough surface No intrusions	Dry slightly weathered
14.1	12/180	Continuous Very tight joints Rough surface No intrusions	Dry unweathered
16	6/70	Continuous Very tight joints Smooth surface No intrusions	Dry moderately weathered
17.7	18/70	Continuous Very tight joints Smooth surface No intrusions	Dry unweathered

20.1	35/50	Continuous Very tight joints Rough surface No intrusions	Dry highly weathered
20.9	10/80	Continuous Tight joints Moderately rough surface 1.5cm Intrusions (Copper Pyrite)	Dry slightly weathered
22.5	30/75	Continuous Very tight joints Moderately rough surface No intrusions	Dry weathered
26.3	25/170	Continuous Very tight joints Rough surface No intrusions	Dry unweathered
27.6	25/50	Continuous Very tight joints Rough surface No intrusions	Dry unweathered
29.6	6/310	Continuous Very tight joints Rough surface No intrusions	Dry unweathered
30.9	10/80	Continuous Very tight joints Rough surface No intrusions	Dry unweathered
33.9	16/170	Continuous Very tight joints Smooth surface No intrusions	Dry unweathered
33.9	36/70	Continuous Very tight joints Smooth surface No intrusions	Dry unweathered
35.5	3/80	Continuous Tight joints (1mm) Rough surface No intrusions	Dry slightly weathered
38.5	20/20	Continuous Very tight joints Smooth surface No intrusions	Dry unweathered
40.2	15/180	Continuous Very tight joints Rough surface No intrusions	Dry weathered
43	10/190	Continuous Very tight joints Smooth surface No intrusions	Dry unweathered
46.3	10/20	Continuous 2mm Separation Moderately rough surface No intrusions	Dry unweathered
47.5	8/80	Continuous Very tight joints Rough surface No intrusions	Dry unweathered
50.5	5/180	Continuous Tight joints (1mm) Rough surface No intrusions	Dry unweathered
53.2	20/180	Continuous Very tight joints Rough surface 4cm Intrusions (Granulitic Quartz)	Dry unweathered
55.2	5/170	Continuous Very tight joints Smooth surface No intrusions	Dry highly weathered

Vein graphite in Bogala is of high purity with 99.9% carbon in-situ in most locations. Degradation and oxidation of carbon is not found due to carbon being less active as a mineral in its natural form.

2.3 Ground water and hydraulic conditions

In Bogala, more than 50% of the operating cost is on dewatering. About 1,000,000 m^3 of water is pumped out per day. Proper mine drainage with adequate measures are taken to prevent or limit water flows downward through crack systems. This way, high cost on mine drainage can be controlled. To combat dust generated in drilling, wet drilling is adopted at Bogala mines, more water is added to the internal network of working areas of the mines. Water seepage from surface cracks adds more water to the underground water inflows. Certainly these water flows can be controlled with due attention given to the maintenance of surface drainage channels. Hence dewatering of water is an act drawing essential management attention in Bogala.

2.4 Economic factors

In Bogala, the grade of ore is very high and the distribution is more or less uniform. Carbon grade of graphite varies from 85% to 99.9%. In earlier times the demand for high grade graphite was high due to World War I and II. The current demand for low grade graphite can be a temporary phase. But, the management should be geared to switch to high grade production whenever the need arises. Currently the discovery of Graphine portends a new phase of in the world graphite industry.

2.5 Comparative mining and processing cost

In Bogala, the mining cost mainly comprises wages, dewatering and supports. Heavy support systems using mainly timber, a yieldable support have to be resorted to the stope environment due to heavy rock fracturing caused by dynamic stresses (Figure 8).

Figure 8: Heavy support system in Bogala. Heavily supported rock piece at Bogala in 260m level.

Due to blasting of the country rock in the process of extracting vein graphite, rock dust is mixed with graphite. Graphite lost as a thin crust in sub grade graphitized rock pieces is removed after crushing and recovery in froth flotation. Lump vein graphite pieces are hand sorted according to different grades and send to mills for size reduction.

The labour force is easily available from the surrounding villages. This has created a strong bond with the villagers. Most of the villagers are descendants of early miners and are dependent on the mine. So there is a long lasting loyalty of the people to the mines.

2.6 Environmental factors

Bogala is situated in a mountainous area and the entry point to the shaft or the pit head is located at a flat level on top of a mountain. The surface has no serious threats due to underground mining except that of the risk of ground subsidence, which can be addressed by good mining skills and efficient support systems.

In the processing plant, the emission of dust is minimized by installing integral dust collectors in the machinery. But practically it is not possible to maintain a 100% dust free working area. The water used for the flotation cells are normally carrying fine graphite particles, which are collected at settling tanks.

The rock pressure increases with depth and dynamic rock stresses peak in stoping environment necessitating installation of heavy re-enforced concrete slabs. These are further strengthened by back filling of rock.

3. Results and Discussion

The results obtained in the research carried out given in Table 7 below gives a clear idea about the totality of the Bogala mining process, which is essential in selecting the best mining method.

Table 7: Results. The data obtained is listed as a table.

Size, Shape	20 to 40cm, Steep dipping veins progressing to depths beyond 600m as to current surveys
Dip/ Dip direction	Na Vein – 65/330 Kumbuk Vein – 75-80/210
Country rock	Metamorphic Garnet Biotite Gneiss
Rock strength	Point Load Index – 11.5 MPa Compressive strength – 143.75 MPa
Planes of weaknesses	There are number of fractures propagating in different directions. Some with mineral intrusions.
Mineralogy	99.9% carbon Graphite
Ground water	Underground seepage , wet drilling and surface water seepage adds water to the mine
Economic factors	High grade carbon with a good grade distribution.
Mining cost	High due to a number of main contributing factors such as rock support, mine drainage and wages
Processing cost	Moderate when compared with other mineral processing costs
Labor	Easily available
Dust	Efficient dust collection facilities in the processing plant incorporated
Water pollution	Addressed by the settling tank.
Preservation of surface	Ground subsidence is minimal to the degree of being totally absent

Considering the results evaluation of mining methods were carried out.

4. Conclusion

As the Bogala mines have a number of restricting factors in choosing a mining method, the best way of accessing the ore will be through a Shaft, which they have already established. The best mining method for a narrow vein would be an open stopping method (as used in Kahatagaha and Ragedara), but with the fractures playing a major role it is not safe to adopt open stopping mining at Bogala.

Therefore after eliminating all the other mining methods, it is clear that the Cut-and-Fill mining method adopted at Bogala is the best method in the circumstance. Through Cut-and-Fill mining method the country rock will get the support to distribute the stresses made by mining and avoid subsidence. Although the cost is high when it comes to supports it is the safest way to mine in Bogala.

5. Recommendations

Since the mining method cannot be changed, to minimize the cost in Bogala they should target at reducing the cost of supports. For this they can be more efficient in reusing the timber and iron. Using sealers to prevent timber from decaying and iron from corroding will ensure more times of reuse.

In the mines there were some places around 260m level, where large pockets of graphite and Vein splitting were found. In these places the mining method has to be innovated a little to overcome them. Concreting will give a permanent solution but with a cost which has to be borne.

Acknowledgement

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