A Study of Underground and Surface Mining Methods in Sri Lanka and its Suitability Assessment

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Abstract

The demand for minerals is rapidly increasing with industrialization, urbanization, and population growth. Sri Lanka has the potential to penetrate the world market with its endowed rich base of minerals despite its small land area. However, selecting a suitable mining method and its optimum utilization have significant roles in the growth of the local mineral mining industry. The lack of systematic approaches in mining methods is suboptimal for the economic growth of Sri Lanka, which demands immediate investigation and reassessment of contemporary mining practices. Thus, this study aims to critique the major mining practices and evaluate their suitability through characteristics and numerical analysis. This investigation was performed for underground mining methods: cut-and-fill stoping and open-stoping; surface mining methods: open-pit, and open-cast placer mining with reference to Bogala, Kahatagaha, Aruwakkalu, and Pulmoddai, respectively. A detailed study complying with the principles of the grounded theory was conducted through a multimethod approach followed by a thematic and content analysis along with the deductive approach. Moreover, the suitability of these methods was evaluated employing the University of British Columbia method through a numerical approach. This study reveals that the selections of mining methods are appropriate for all four mines, and mining practices are modernized and traditional, complying with site-specific requirements.

Keywords: Cut and fill stoping, Mining methods, Open pit, Open stoping, Placer mining

1. Introduction

Despite its small area, Sri Lanka is bestowed with abundant mineral resources and has a long mining history over several centuries [1], [2]. Mineral resources of Sri Lanka such as gems, graphite, and titanium-bearing sand have a greater demand in the world market due to their higher grade. Subsequently, mining and quarrying have contributed over 2.1 per cent to the Gross Domestic Product (GDP) in the past five years [3]. However, the contribution of mining to the country's economic growth has been suboptimal due to the lack of systematic approaches. Even though modernised and traditional mineral mines exist in Sri Lanka and practice a vast range of mining methods, notably, some deposits have not been optimally engineered and exploited fully to their existing potential.

The mining method is selected based on the respective geology of the deposit, hardness of the ore and host rock, depth, thickness, and other geological aspects [4]. Further, the extraction of narrow, steeply dipping vein deposits and deposits at great depth is significantly challenging and requires specific mining techniques. Thus, the mining methods adopted can be categorised into underground and surface mining methods.

Appropriate mining method selection and its optimum utilisation play a significant role in the success of the local mineral mining industry. Besides, incompetent mining practices constrict productivity and limit access to future reserves while damaging the environment. However, in the Sri Lankan context, there is a lack of comprehensive studies on existing mining practices. Thus, this study converges the characteristics and numerical approaches in analysing the suitability and practices of selected mining methods.

2. Methodology

2.1 Site Selection

This study focuses on the significant large-scale operational mines in Sri Lanka to represent underground mines: Bogala and Kahatagaha and surface mines: Aruwakkalu and Pulmoddai.

2.1.1 Bogala Mines

Bogala is a narrow vein graphite mine in operation since the mid-19th century, which extends up to 476 m depth. Moreover, it produces world-class graphite of 99 per cent purity. This underground mine is owned by Bogala Graphite Lanka PLC and is situated in Arugammana, Kegalle.

2.1.2 Kahatagaha Mine

Kahatagaha graphite mine is the deepest among underground mines in Sri Lanka, reaching a depth of 670 m. Further, this state-owned mine operates under Kahatagaha Graphite Lanka Limited and is situated at Maduragoda-Dodangaslanda, Kurunegala.

2.1.3 Aruwakkalu Limestone Quarry

Aruwakkalu Limestone Quarry is the fully mechanised and largest open-pit mine in Sri Lanka managed by Siam City Cement Lanka Limited. Further, it is located in Eluwankulam, Puttalam.

2.1.4 Pulmoddai Placer Deposit

Pulmoddai placer deposit is a source of predominant heavy minerals sand, which extends for 7 km along the Eastern coastal belt of Sri Lanka. Moreover, it is managed by state-owned Lanka Minerals Sands Limited.

2.2 Data Collection and Analysis

Existing underground and surface mining methods practiced in the selected mines were subjected to a detailed study complying with the principles of the grounded theory through a multimethod approach, comprising semi-structured interviews, participant and non-participant observations, and document analysis. The semi-structured interview method was followed with the objective of formal data acquisition. Moreover, questions were prepared intentionally standardised open-ended for more depth and clarified answers. Further, direct structured participant field investigations at Bogala and Aruwakkalu and direct structured non-participant investigations at Kahatagaha and Pulmodai were conducted to acquire information on the mining practices. The gathered data from these acquisition methods were subjected to a thematic and content analysis along with the deductive approach.

2.3 Suitability Assessment

Outcomes from the data analysis were critically assessed, and the suitability of the mining methods practices at each site was evaluated. Further, mining method selection criteria: University of British Columbia (UBC) method [5] was utilised to evaluate the mining methods at Bogala, Kahatagaha, and Aruwakkalu. The inputs were given for geometry and grade distribution, such as general shape, ore thickness, ore plunge, grade distribution, and depth in accordance with the gathered data. Further, the suitability rankings of mining methods were estimated through the generated numerical rating.

3. Results and Discussion

3.1 Evaluation through UBC Method

Table 1: Numerical ratings from UBC method evaluation.

Mining Method	UBC Rating		
	BO	KH	AR
Block Caving	-38	-38	9
Cut and Fill Stoping	18	18	14
Longwall Mining	-37	-37	11
Open Pit	-42	-42	15
Room and Pillar	-37	-37	14
Shrinkage Stoping	16	16	-40
Square Set Stoping	10	10	7
Sublevel Caving	-37	-37	10
Sublevel Stoping	4	4	16
Top Slicing	5	5	9

Where BO = Bogala, KH = Kahatagaha, and AR = Aruwakkalu

3.2 Cut and Fill Stoping

Bogala adapted open stoping at its earlier stage and has been replaced with the overhand cut-and-fill stoping method beyond the depth of 165 m below the pit head level [6]. Presently, it is the only underground mine in Sri Lanka that practices the cut-and-fill mining method.

Table 2: Characteristics of Bogala mines (after Hettiwatte, 2014) [7].

General Shape	Steeply dipping narrow vein
Depth	> 500 m
Thickness of Ore	20 - 40 cm
Dip/Dip Direction	Na vein: 65/330
	Kumbuk vein: 75-80/210
Mineralogy	99.9% carbon graphite
Host Rock	Metamorphic Garnet-biotite gneiss
Rock Strength	Compressive strength - 143.75 MPa
Planes of Weaknesses	Number of fractures propagating in different directions
Groundwater conditions	Underground seepages - Wet mine
Economic Factors	High-grade graphite with good grade distribution
Labour	Easily available
Environmental Concerns	Dust control by wet drilling
	Water pollution is low
	Ground subsidence is minimal/totally absent

Bogala is a wet mine scoring 4 for groundwater conditions in RMR rating as it has the possibility of water ingress through the fractured planes. Moreover, the RMR of this mine is 71 due to the lower ratings for the condition and orientation of joints and groundwater [7]. Further, Table 2 endorse that the most suitable mining method to extract steeply dipping narrow vein graphite from Bogala underground mine is cut-and-fill stoping as the country rock is highly fractured and incompetent. Furthermore, the numerical rating of the UBC method validates its suitability with the rating of 18, as shown in Table 1.

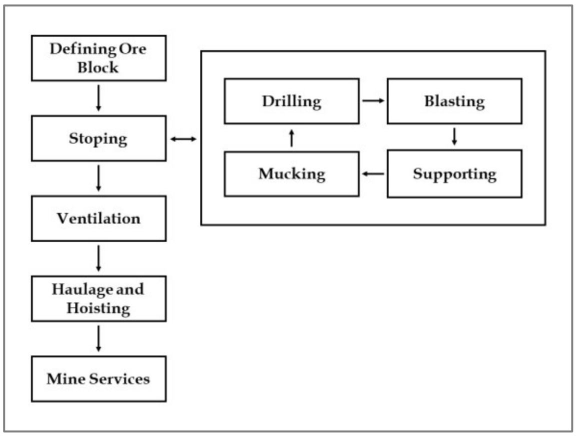

Figure 1: Mining flowsheet at Bogala.

In addition, Bogala practices this overhand cut-and-fill stoping through a cyclic process with the aid of other supportive services, as shown in Fig. 1.

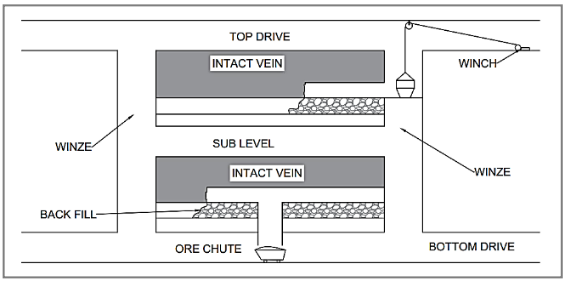

Figure 2: Conceptual diagram of ore block at Bogala.

An ore block is bounded by two drives and winzes comprising an area of 60 m x 60 m, as illustrated in Fig. 2. It permits simultaneous stoping, maximum ore recovery, efficient haulage and hoisting, adequate ventilation, and reasonable ground control. Subsequently, stoping initiates from the lower main level of the block with the dimension of 1.8 m x 1.3 m and progresses upwards. This optimal stope dimension opens the way for man passage and haulage of materials in the narrow vein environment.

Notably, stope advances through a mining cycle: drilling, blasting, mucking, and supporting, as exhibited in Fig. 1. Usually, a pneumatic-powered jackleg drill having 3 feet drilling rod with a chisel bit or button bit of 34 mm diameter is used to drill graphite ore and intact rock. Moreover, water-gel and ANFO (ammonium nitrate with fuel oil) are used as primary and secondary explosives, respectively, along with the electric detonators (ED) to initiate the blast. Immediately after, scaling is performed using a steel bar or high-pressure water jet to ensure the workplace's safety from the loosening of rocks. In addition, roof support is established using timber logs or S-H rails and wooden planks before approaching the blasted face. Mucking is carried out manually using hands to maximise the ore recovery.

Furthermore, the ventilation network of the Bogala mines is supported by an exhaust ventilation system. However, workplaces are not exposed to the main ventilation network; thus, compressed air is used to provide comfort for workers [8]. Moreover, winzes and ore chutes are used for ore haulage, and the materials are transferred to the surface through the Alfred and Gabriel shafts. In addition, a dedicated team upholds uninterrupted mine services.

3.3 Open Stoping

Kahatagaha has a vast range of parallel graphite veins in the East-West direction with southerly dip and practices the conventional open-stoping method to extract the higher-grade graphite ore.

Table 3: Characteristics of Kahatagaha mine.

General Shape	Steeply dipping narrow vein
Depth	> 600 m
Thickness of Ore	10 – 25 cm
Dip	60° - 70°
Mineralogy	99.9% carbon graphite
Host Rock	Garnet granulitic gneiss
Rock Strength	Compressive strength - 123.75 MPa
Planes of Weaknesses	Competent rock
Groundwater conditions	Dry mine
Economic Factors	High-grade graphite with good grade distribution
Labour	Easily available
Environmental Concerns	Dust control by wet drilling
	Water pollution is low
	Ground subsidence is minimal/totally absent

Kahatagaha is a dry mine as the groundwater conditions are categorised under the damp condition with the rating of 10 in the RMR classification system. Moreover, the host rock of Kahatagaha is classified as a very good rock under the Class I category, and RMR is determined to be 97 as it possesses a higher rating for condition and orientation of joints and groundwater [7]. In addition, Table 3 depicts that the characteristics of Kahatagaha are favourable for open stoping, even though UBC ratings recommend cut-and-fill stoping with the value of 18, as shown in Table 1. It is evident that open stoping is more cost-effective than cut and fill stoping for the mines with good ground control.

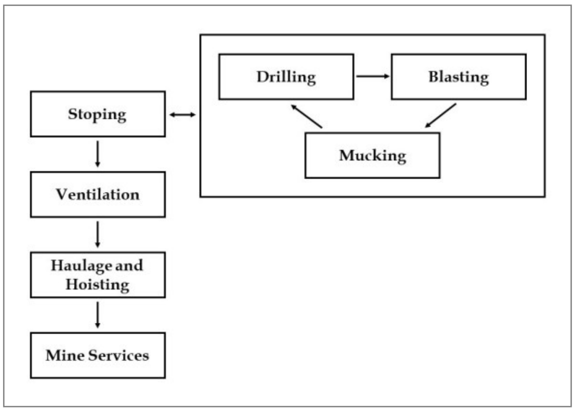

Figure 3: Mining flowsheet at Kahatagaha.

Further, Kahatagaha follows the mining practices, as shown in Fig. 3. Stoping progresses upwards from the main drift using the overhand method while the stoping width varies from 20 cm to 50 cm.

Conventional drilling and blasting is practiced for the extraction, and on most occasions, only the graphite veins are extracted without creating space for man passage. Albeit it reduces the cost for barren rock disposal, it halts the maximum ore recovery. A steel rod 'Kuththu' is used to drill the graphite ore manually, and a pneumatic-powered jackleg drill is used for mechanised drilling of intact rock. Although manual drilling consumes a longer time, it contributes to the maximum recovery of the narrow vein with a lower ore dilution.

No benching system exists on stopes, and the men work by standing on anchors fixed on the footwall, which may reduce the production efficiency and safety. Occasionally, wooden planks are placed on the anchors across the stope to provide a working platform. A blast hole of 36 mm diameter is charged with water-gel and ANFO as primary and secondary explosives, respectively, and the blast is initiated by a combination of plain detonator and safety fuse.

Figure 4: Unloading from 'Winch Box' at Kahatagaha mine.

The blasted ore is piled up in the drift and mucked manually by the hands. After that, it is packed in gunny bags and hoisted to the surface. Level-to-level hoisting is done using 2 feet x 2 feet x 2 feet dimensioned wooden boxes called 'Winch Box,' as shown in Fig. 4. However, the existing infrastructure developments are not optimised to meet the production demand as it consumes much time for haulage and hoisting.

Further, the mine is ventilated by an exhaust ventilation system, comprising a main downcast shaft: Kahatagaha, upcast shaft: Kolangaha, and five booster fans at the return airways. However, open-stoping is a disadvantage in ventilating deeper levels, as air leakage and short-circuits are dominant through mined-out areas. Thus, the temperature below 2000 feet level rises and may reduce workers' efficiency.

3.3 Open Pit Mining

Aruwakkalu limestone deposits are found beneath the thick overburden layer of red soil, and the limestone is extracted by the open-pit mining method.

The limestone deposit is laterally extended in a shallower depth less than 70 m with an overburden thickness of modestly 25 m to 30 m, as given in Table 4. Thus, the open-pit mining method is economically viable as the ore is easily accessible by removing the overburden. In addition, results from the UBC method recommend the open-pit mining method with a score of 15, as depicted in Table 1, which validates the suitability of the existing mining method. Although the UBC method rates the underground method: sublevel stoping at the top, it is not feasible as it demands competent ground control.

Table 4: Characteristics of Aruwakkalu mine.

General Shape	Horizontally bedded deposit
Depth	< 70 m
Thickness of Ore	9 – 12 m
Mineralogy	Miocene Limestone
Overburden	Red soil (25 - 30 m)
Inter-burden	Kartsified limestone (12 - 15 m)
Groundwater conditions	Mining above mean sea level
Economic Factors	Raw material for cement production
Labour	Easily available
Environmental Concerns	Animal rescue
	Restoration of flora

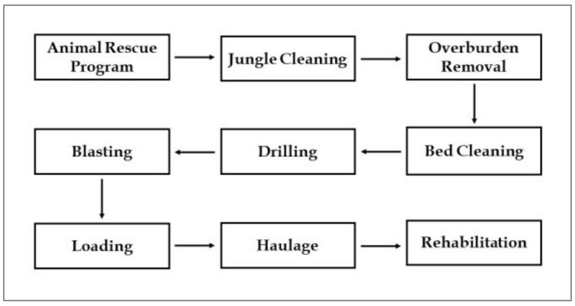

Figure 5: Mining flowsheet at Aruwakkalu.

Mining practices at Aruwakkalu limestone quarry are proceeded, as indicated in Fig. 5. The quarry management carries out a detailed study at the beginning on the area's ecology, flora, and fauna. Further, jungle cleaning is followed by removing the overburden consist of red soil and low-grade limestone layers. Moreover, mining progresses by advancing the benching system to form the open pit, as shown in Fig. 6, until it reaches the limestone bed with an ideal lime saturation factor (LSF) as the cut-off grade.

Figure 6: Aerial view of Aruwakkalu mine.

The pit is developed with a 3.5 - 3.8 stripping ratio by multi-benching (5 - 7 benches) on the red soil layer, with 2.1 m bench height, 4 m bench width, and 90° slope angle. The 40 per cent of the intermediate layer is removed by ripping and dozing, and the rest is extracted by blasting. Ripping and dozing is highly preferred in the soft parts of the Karstified layer as it is comparatively cheaper than drilling and blasting. Further, the high-grade limestone is extracted by drilling and blasting as the hardness of the layers increases with depth. Furthermore, the drilling is performed using hydraulic drill machines to 10.3 m depth with a drill hole diameter of 76 mm. Moreover, water-gel and ANFO are charged along with electric detonators in a staggered pattern with spacing: 2.8 m and burden: 2.5 m.

The blasted material is loaded using a hydraulic shovel of 4.8 m^3 bucket capacity and hauled to the dumpsite located 2.5 km away from the pit using dump trucks of 55 tonnes payload each. Moreover, rehabilitation progresses simultaneously along with the mining by refilling the pits and reforesting the preserved species to ensure the safe locomotion of the native wild animals.

3.4 Open Cast Placer Mining

Pulmoddai placer deposits are among the richest occurrences of the heavy mineral sand along the beach from Nilaweli to Mullaitivu in Eastern Sri Lanka. The pre-mining resource was estimated as 12.5 million tonnes averaging 90 per cent heavy minerals, and the average assemblage comprises 65 per cent ilmenite and leucoxene, 10 per cent zircon, and 10 per cent rutile [9]. The remaining non-valuable heavy minerals are predominantly monazite, garnet, and sillimanite. These heavy minerals are extracted using the mechanised open cast mining method.

Table 5: Characteristics of Pulmoddai deposit.

Deposit type	Replenishable beach placer
Length	7 km
Width	100 m (only 30 m is minable)
Major Heavy Mineral Content	Ilmenite, Rutile, Garnet
Climatic conditions	Heavy rain during North-east monsoon
Economic Factors	Raw material for titanium products
Labour	Easily available
Environmental Concerns	Beach erosion
	Affect flora along the shoreline

The deposit covers an area of 18 hectares (0.18 km^2) which extends along the beach for 7.2 km with an average width of 50 m, while the maximum width is 250 m [9], [10]. Pulmoddai practices a mechanised open cast mining method as the deposit is easily scrapable using machines with a higher mechanical and economic efficiency, and the site characteristics are tabulated in Table 5. Further, there is high uncertainty in the deposition of heavy minerals as it is naturally replenishable and time-dependent. Thus, an increment in the mining rate may deplete the grade of mineral sand. It is evident that the mechanised open cast mining method is the most suitable method to extract mineral sand.

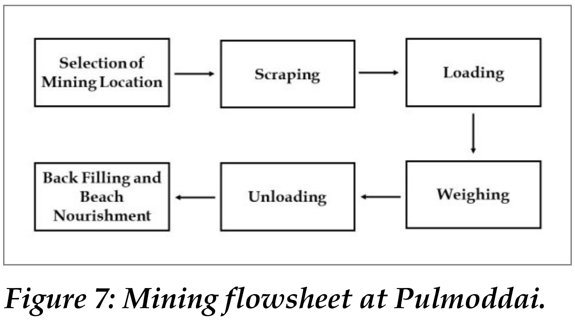

Figure 7: Mining flowsheet at Pulmoddai.

The mining sequence at the Pulmoddai placer deposit is indicated in Fig. 7. The processing plant at Pulmoddai is designed to operate with a minimum grade of 40 per cent. Thus, viable mining locations are selected from the laboratory testing of auger samples collected along the shore to satisfy the above requirement. Meanwhile, it is required to maintain face angle of beach slope between 10° to 12.5° for ilmenite entrainment (70-79 wt%) and between 12° to 14.5° for garnet deposition (20-29 wt%) [11]. However, it is hard to establish this face angle along with the dynamic wave actions.

Figure 8: Mechanical scraping operation at Pulmoddai using wheel loader.

A thickness of 0.5 – 2 feet (0.15 - 0.61 m) beach placer along the shore in predetermined locations are scraped using the mechanical loaders as shown in Fig. 8 with a bucket capacity of 0.75 cubes (2 m^3). Further, mined raw mineral sand is hauled in wet condition using private tractors with a trailer capacity of 1.5 cubes (4 m^3). After that, it is unloaded to the pile near the processing plant, preceded by weighing at the measuring point. However, during the Northeast monsoon period, limited mining activities occurred due to heavy rain in the Pulmoddai zone as the waves get rough and cause an unsuitable environment for mining.

4. Conclusion

This study underlined the mining methods: cut-and-fill stoping, open-stoping, open-pit, and open-cast placer mining, practises at Bogala, Kahatagaha, Aruwakkalu, and Pulmoddai, respectively, are suitable according to the site characteristics and numerical evaluation results of the UBC method. Further, all these four mines adapt a cyclic process for mining, aligned with the predefined flowsheets. Moreover, it is highlighted that hybrid modernised-traditional approaches in mining methods at these mines comply with the site-specific requirements.

5. Recommendations

It is recommended to carry out advanced numerical analysis to validate the suitability of practising mining methods meticulously.

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