Critical Evaluation of Most Suitable Underground Mining Method for Kahatagaha Underground Graphite Mine - A Case Study

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Abstract
Sri Lanka has been a well-known natural vein graphite supplier to the world since 1820. This reputation is mainly due to its extremely high purity, the purity being above 99% carbon as in-situ status and no other country in the world has vein graphite deposits for commercial mining now. Vein graphite is mined at Kahatagaha, Bogala, Ragedara and also from a few smaller underground mines in Sri Lanka. For decades, the Kahatagaha graphite mine has been practising the ‘open stope mining method’ and this method itself does not require extensive mine support because high strength of host rock inside the mine. It can be thought that the behaviour of graphite veins especially inclined in nature and stable host rock could be the main factors to select above mentioned mining method. But, this mining method causes many practical issues now so that mine production, miners` safety and underground work supervision are badly affected. This research includes the study of the current mining method adopted at Kahatagaha graphite mine and its suitability compared with other mining methods used for narrow vein mining and proposing a mining method which is more suitable, safer, and more economical compared to the current practising method.

Keywords: Cut & fill method, Open stoping, Vein graphite

1 Introduction

The existence of graphite in Sri Lanka (then known as Ceylon) has been known since 1675 when the Dutch governor, mentions the existence of veins in the hills and maritime provinces.

Substantial graphite mining and export of graphite in Sri Lanka began in 1824 with graphite exports peaking in 1899.

Sri Lanka is the only country known to extract and produce commercially viable quantities of crystalline vein graphite [1]. Crystalline vein graphite is believed to be a naturally occurring pyrolytic graphite condensed from gas or liquid phase under high temperature and pressure well below the earth's crust [2]. Deposits consist of veins of variable thickness and various carbon content ranging from 80% to 99%. In Sri Lanka, Bogala graphite mines and Kahatagaha graphite mine are famous underground mines and the largest natural graphite producers, which supply natural vein graphite in various product categories to the international graphite market.

Kahatagaha graphite mines are the deepest underground mine in Sri Lanka. The depth of the mine is 2080 feet whereas the depth of the Bogala graphite mine is 1650 feet [1]. In both mines, it can be observed narrow graphite veins thickness varying from 5 mm to 100 mm are dipping downwards steeply, slightly vertically or inclined manner. Narrow vein mining is one particular area of mining and is defined as mining operations involving orebodies or veins with a true thickness of less than 4 m. In Bogala mines and Kahatagaha mines, the cut and fill mining method and open stoping mining method are being practised respectively.

Selecting a mining method for mining moderately deep ore bodies can be a complex process due to many factors required for evaluation. Such factors include but are not limited to the following: shape, dip, grade, depth and rock mechanic properties of the ore-body and surrounding rock medium [2]. Several factors influence the selection of a mining method: physical, mechanical and chemical characteristics of an ore body and its host rock (compressive strength, weak planes, groundwater, mineralogy etc.); the value of mineral and grade; geometry of the deposit (thickness, size, shape and depth); labour (skilled and un-skilled); technology; environmental considerations; markets; production rate and availability of finance and capital [1]. There are cases in certain underground mines where due to selecting improper mining methods, mines had to close. In practice, there are cases in which the mining and geological factors allow the application of a certain mining method, but its application is not justified from the aspect of economic effects. There are also cases in which a certain mining method considers the application of certain types of machinery, but it is not justified by mining technical factors [2]. A few years ago, one Sri Lankan underground graphite mine tried to apply a raising method to extract graphite as it saves time, and energy and increases productivity. However, due to various practical difficulties encountered during the raising operation, that method had to be abandoned.

2 Literature review

As per the literature, a wide range of mining methods has been developed or adapted to exploit narrow mineral ore bodies or veins. Narrow graphite veins as found in Kahatagaha graphite mines or Bogala mines, there are particular issues when selecting the most suitable mining method associated with generally small workplaces available, and to suit a variety of geotechnical environments and the full range of orebody dips from horizontal to vertical and each of the methods has advantages and disadvantages. So, these should be considered in feasibility studies, or as part of selecting the best option for any particular underground mine [3].

2.1 Mining methods adapted to extract narrow vein ore bodies

In developing countries, labour costs are often relatively low, so the level of mechanization is often minimal. Some of the mining methods are not significantly different to those that were used in antiquity. Artisanal workings, common in developing countries, generally involve manual breakage and loading of ore. This is often in very poor working conditions in terms of ventilation, ground support and personal protective equipment (PPE), with associated high injury and mortality rates.

In more advanced economies, with high labour costs, mechanization is usually attractive as it enables increased productivity and improved safety. Where possible, the equipment and techniques and thicker orebodies or mineral veins have been adapted to suit more confined workspace. Manual operations can be assigned in narrow ore bodies where the working environment is conducive to the health and safety of miners. Some of the more commonly used mining methods adapted for narrow vein mining are discussed below in terms of their key technical and operational features, and advantages and disadvantages with particular reference to geotechnical issues.

2.1.1 Open stoping method

Stope faces and side walls remain unsupported during ore extraction, while support for the country rock is developed as pillars are generated by stoping [4]. The pillars may be left in place or extracted at a later time. Big hole stoping is a larger-scale variant of sublevel open stoping that uses longer blast holes. This results in vertical spacings between sublevels of up to 60 m instead of 40 m for sublevel open stoping. Sublevel open stoping is applied in massive or steeply dipping stratiform orebodies. For an inclined orebody, the inclination of the stope footwall must exceed the angle of repose of the fragmented rock to promote the free flow of rock through the stope to the extraction horizon. Since stopes in these methods are unsupported, the strength of the orebody and surrounding rock mass must be sufficient to provide stable walls, faces, and crowns for stope excavations. Additionally, the orebody boundary must be regular to minimise dilution. Due to the blast hole drilling and blasting technique, the minimum orebody width for open stoping is approximately 6 m [3]. Pillar recovery is a common practice in open stoping, made possible by the use of backfill placed into primary stope voids. The backfill replaces the support provided by the ore pillar, allowing for pillar extraction. The ability to supervise the working place, access path, and safety of miners during drilling and mucking is comparatively low in this method.

2.1.2 Cut & fill method

Cut-and-fill mining is a very versatile method that can be adapted to an orebody with any shape. It is a very selective mining method that most commonly advances up-dip in an inclined orebody. Mining costs are relatively high compared to other methods; recovery is also high, and dilution is low. As such, it is an appropriate method for high-grade orebodies [4]. In addition, the cut-and-fill mining method is a very controlled cycle of mining that is repeated many times in a single deposit. The simplified steps of this method are drilling and blasting, scaling, and support, where loose rock is removed from the stope crown and walls and lightweight support is installed. Other related activities are ore loading and transport, where ore is mechanically transported in the stope to an ore pass and backfilling, where a layer of backfill with a depth equal to the thickness of the ore slice is placed on the stope floor [5].

The success of this method depends on the continued stability of the rock mass surrounding the work area where miners work continuously. This is achieved through controlled blasting, application of local rock support, and more general ground control using backfill. The cut-and-fill mining method is applied in veins, inclined tabular orebodies, and massive deposits. When mining a large enough orebody, mining can be divided into multiple sections separated by vertical pillars. This method is suitable for orebodies dipping 35-90 degrees in either shallow or deep locations. The backfill allows for weaker country rock, but the orebody itself must be a competent rock mass. However, if the orebody strength is very poor, a variation on cut-and-fill, underhand cut-and-fill, may be used. The ore grade must be sufficiently high to withstand dilution from backfill, but the grade can also be variable since lenses below the cut-off grade can be left unmined [3]. The cut-and-fill method has been widely used in narrow vein ore bodies throughout the world. Although a wide range of variants exist, most methods involve mining an initial horizontal "stope" drive along the orebody, which is subsequently filled with unwanted rock generated due to blasting to provide a working platform or floor for the next cut or stope. The orebody is extracted by a series of successive stopes working up-dip. This is described as the 'overhand' cut and fill method. Even though this method gives more safety working area for miners, this method requires additional underground supporting material such as timber logs, planks, iron ladders etc.

2.1.3 Narrow vein bench stoping

This method is applied where ground conditions are suitable for extracting the mineral safely and the ore body is sufficiently continuous and regular (planar) to allow the use of long-hole methods. The economic advantages of long-hole bench stoping over the alternatives are usually compelling.

Generally, the method has been applied to steeply dipping ore bodies (> 60^0 dips). Under this method, where good ground conditions are present in the hanging walls and foot walls, it has been possible (with careful drill and blast practice) to mine stopes that are significantly narrower than the minimum ore drive width [1].

2.1.4 Up dip bench stoping

This method has been widely used in orebodies up to 15 m true thickness as well as very narrow ore bodies, down to a minimum mining width of about 1 m where ground conditions allow. In very narrow orebodies, the ore drives used to access and extract the ore are usually driven at the minimum width required by the equipment [1].

2.1.5 Down dip bench stoping

This method has also been used in many underground mines having narrow vein systems. Horizontal ore drives (sublevels) are driven at typically 15-20 m vertical intervals. Blast holes (up holes) are drilled from the drives and fired into a slot.

Based on different methodologies applied in each mining method, it is a crucial decision to adopt a more suitable mining method for a particular underground mine. Sometimes, the adopted mining method is slightly changed or changed depending on the situation in some underground working levels.

2.1.6 Current practise of underground graphite extraction in Kahatagaha mines

For years, Kahatagaha graphite mine has been practising the 'open stope mining method' and this method itself does not require extensive mine support because high strength of host rock inside the mine and there is less fracture propagation as well [1]. During the graphite extraction process, sometimes both graphite and part of wall rock are mined out to enable sufficient working space for miners. In certain places of working locations, cap support installations are used to counteract the stresses created due to mine excavations.

Below Fig. 1 shows how open stoping mining method is practiced in Kahatagaha. Minimum supports have been used for extraction and no proper working platform. No roof supports have been fixed as well.

Figure 1: Open stoping mining method in Kahatagaha graphite mine

3.1 Identified issues related to mining method in Kahatagaha mines

When analysing all aspects of the current mining method, achieving graphite production targets, underground mine development and mine safety of Kahatagaha graphite mine, it is well observed that the mining method now practising in the mine has caused great impact, so it is the utmost requirement to revisit the present system and go for another more suitable mining method.

The identified problems of the mining method practised in the Kahatagaha mine are as follows:

1. Waste rock cannot be used for re-filling voids created due to excavation, so all waste rock needs to be moved to the main level for hoisting up to the surface.
2. Accessibility to the working face is very difficult which directly affects the supervision.
3. Risk is very high when visiting workplaces especially as there are no secured access paths using ladders and platforms.
4. A certain portion of graphite is kept as supporting pillars or kept as it is due to the inability to reach the vein.
5. Very low productivity of graphite extraction as miners cannot do their work comfortably standing or staying at the workplace.
6. Impossible to predict the estimated monthly target due to the nature of working place.
7. Ore reserve estimation is impossible because no clear ore-blocking system is maintained with the current mining method.
8. The entire ore block cannot be extracted as some pillars are required to be kept for side wall stability.

3.2 Proposed mining method of graphite extraction

Out of all adapted mining methods for extracting narrow vein ore bodies, the most suitable mining method for the Kahatagaha mine can be recommended as the overhand cut and fill mining method, especially for certain selected locations at 2000 ft level and below levels to be developed in the future. The graphite veins found at such levels are 75^0 to 85^0 steeply dipping, these veins can be extracted by a series of successive stopes (benches) working in pre-prepared ore block. This method has been widely used in narrow orebodies throughout the world. No one has initiated this method so far in this mine and the same method i.e., open stoping method, which is somewhat primitive now has been adopted and carried out for decades. This primitive method had been applied for shallow veins in Kahatagaha mines, which were found to be not steeply dipping veins. However, the behaviour of the veins changed, and the same method has been applied without thinking about a more suitable way of extraction graphite.

Below Fig. 2 shows how the proposed mining method was applied in the Kahatagaha mine. In this system, an ore block is created in between two underground drives and two winzes. Rom lower drive, step-by-step stoping levels are formed as shown in Fig. 2 until the entire block is extracted.

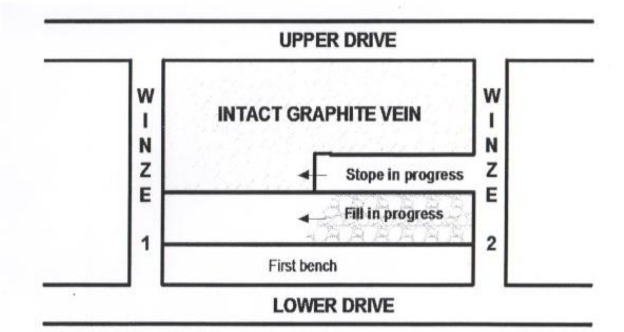

Figure 2: Schematic diagram of the proposed mining method

Advantages of the cut & fill mining method

1. Waste rock can be used for re-filling void spaces generated due to excavation. So minimum interruptions

for hoisting graphite with available hoisting system.
2. Clear access path to the working place so easy supervision.
3. Mine stability is highly ensured.
4. The entire working place is safe for miners as the roof is supported, the working floor is stable and there is sufficient space for working.
5. Provision of ventilation to the working place is comparatively easy.
6. The entire graphite block can be extracted.
7. Easy to estimate ore reserve.
8. Graphite can be taken out with minimum dilution.
9. Supporting material can be re-used in some instances.
10. Productivity of each underground production group can be increased with increased production.
11. Mine planning is easy after some time once this method is executed.
12. Training miners for this method is much easier than open stoping method.

Disadvantages of the cut & fill mining method

1. Additional fixing material is required (Timber logs, timber planks and SH rails, steel supports) compared to existing method in the mine.
2. Additional quantities of explosive material required (Both additional costs incurred in 1. & 2. can be compromised with increased production).
3. Familiarization with the new method takes some time.

Considering the above advantages and disadvantages of the proposed mining method, it can be applied as a pilot project of one selected ore reserve block as an initial step and extend the same method in other ore reserve blocks below 2000 ft level.

4 Discussion

Even though Kahatagaha graphite mines adopted open stoping method for extracting graphite from narrow veins, basically it is not safe and with many disadvantages factors already identified in this research. When considering other vein mining methods used internationally, the veins are big, and all the mining methods are mechanized and are on the verge of transforming to automation. Almost all of them use heavy machinery inside the mine itself for extracting and transporting the minerals. But in Kahatagaha mine, it is not possible as the veins are thin and making large openings is not economical. Therefore, considering the advantages and disadvantages related to the proposed mining method, it is clear that the cut & fill mining method can be adopted in Kahatagaha graphite mines especially where veins show nearly vertical or vertical behaviour.

5 Conclusions

Even though Kahatagaha graphite mines have been practising the open stoping mining method for years, in terms of safety, efficiency and economy of graphite mining, it can be emphasized with all benefits of the proposed mining method mentioned in this study, it is high time to switch on to new mining method i.e. over hand cut & fill mining method. This method can be easily applied below and above veins at 2000 feet underground level. In the long term, when the mine goes deeper and deeper levels, applying this new mining method may give substantial benefits in many ways.

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