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Development of Safe and Sustainable Mining Methods for Artisanal and Small-Scale Gold Mining Operations Exploiting Alluvial or Colluvial Deposits with Hard Rock Potentials

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Abstract

Artisanal and Small-Scale Gold Mining (ASGM) operations are known to contribute significantly towards rural economic development. The operations which are widespread in about 80 countries across Africa, Asia, Oceania, Central and South America have the potentials to alleviate poverty, create employment opportunities, generate income and produce large quantities of the precious mineral gold. In spite of all these potentials, the sector is associated with high levels of environmental degradation, health and safety threats and low productivity that threaten the sustainability of the sector. These challenges have been linked to the use of inappropriate mining methods for the various deposit types exploited. In mining engineering principle, the selection of a suitable mining method for a particular ore deposit is critical for the environmental, safety and economic sustainability of a mining project. However, little attention has been given to the subject of sustainable mining methods for ASGM operations. This study seeks to fill the gap in science by developing safe and sustainable mining methods for ASGM operations exploiting alluvial or colluvial deposits with hard rock potentials. These particular deposit types have been chosen because they are the most exploited deposit types by ASGM miners. The methods used in conducting this study include literature review of the occurrence of these deposit types. Field visits to 3 ASGM sites in Ghana exploiting these deposit types and evaluation of the challenges regarding the mining methods being used. The development and design of the mining methods were done using Surpac 6.6.2 software and design tools in Microsoft PowerPoint. Results from the study indicated that there is a gap in literature regarding ASGM mining methods and a gap in the miners' knowledge about the appropriate mining methods tailored for their deposit types. Moreover, the wide pits which were used to exploit the deposits posed safety risks, had low productivity and limited access to deeper hard rock deposits. This study aims to bridge the existing knowledge gap by developing the Bench Pit-Underground Mining (BPUM) method, designed specifically for ASGM operations exploiting these deposit types. It is therefore recommended ASGM operations adopt the BPUM method to ensure safety, increased productivity and sustainability in their operations.

Keywords

Mining Methods, Artisanal and Small-Scale Gold Mining, Sustainability, Environmental Degradation, Safety

1. Introduction

The features which are used to characterize Artisanal and Small-Scale Gold Mining (ASGM) operations globally include: the poverty-driven nature; selectivity of deposits; use of inappropriate and unsafe mining methods; poor mineral extraction techniques; low levels of technology; low productivity levels; poor management and entrepreneurial skills; lack of skilled labour; poor regulations and monitoring; low financial resources; high manual employment opportunities; informalities of operations; gender marginalization; child labour; negative environmental, safety, security, social and economic impacts (Davidson, 1993; Dreschler, 2001; Hentschel, Hruschka, & Priester, 2002; Aryee, Ntibery, & Atorkui, 2003; Hentschel, Hruschka, & Priester, 2003; Asamoah & Osei-Kojo, 2016; Bansah, Yalley, & Dumakor-Dupey, 2016; McQuilken & Hilson, 2016; Hilson & Maconachie, 2017; Fritz et al., 2018; Gyan, 2019; Sidorenko, Sairinen, & Moore, 2020). Although ASGM operations come in different forms in different countries, they share similar characteristics, which makes them easily identifiable. Salati, Mireku-Gyimah, & Eshun (2016) emphasized that a distinction could be drawn between Large Scale Gold Mining (LSGM) operations and ASGM operations based on the modes of organization and coordination of operations. The LSGM operations are well planned and designed, systematically operated and centrally coordinated unlike the improperly organized and haphazardly operated ASGM sector (Salati, Mireku-Gyimah, & Eshun, 2016).

ASGM is an important sector within the mining industry as the sector produces over 20% of the total global gold production (Fritz et al., 2018). It is known to support various economies, especially in the developing countries where such operations are dominant (Hentschel, Hruschka, & Priester, 2002; Avila, 2003; Hilson & Maconachie, 2017). Contributions to economic growth come in the form of employment generation, gold production, revenue generation from the sale of gold, taxes and royalties payments, licensing and permits fees, promotion of local businesses and poverty alleviation (Hentschel, Hruschka, & Priester, 2002; Donkor et al., 2006; Kessey & Arko, 2013; Bansah et al., 2018; Asamoah & Osei-Kojo, 2016; Bansah, Yalley, & Dumakor-Dupey, 2016; Bansah, Dumakor-Dupey, & Sakyi-Addo, 2017). It is also known to be an alternative for mining relatively smaller gold deposits, which otherwise would not be viable mining by LSGM techniques. In the more organized operations, ASGM operations engage in Corporate Social Responsibilities (CSR), community development and sustainability projects. The increment in ASGM operations globally is linked to the rising gold price, difficulty in earning sustainable incomes from agriculture and other rural businesses, massive retrenchments in LSGM operations, collapse of LSGM operations and the urge for individuals to escape poverty and "get-rich-quickly" (Asamoah & Osei-Kojo, 2016; Bansah, Yalley, & Dumakor-Dupey, 2016; Fritz et al., 2018).

However, analysis of the operations indicates that poor mining techniques and technologies are employed which result in low production levels, negative environmental, safety, social and economic impacts. The poor mining techniques and technology are adopted because the Artisanal and Small-Scale Gold Miners (ASGMrs) lack the expertise and skills to carry out mining in an optimized and sustainable manner. Many of these miners are illiterates with the few literates lacking basic knowledge and skills in sustainable mining operations. Moreover, there is the problem of availability of mining techniques and technology exclusively for the sector whereas the few known techniques and technologies are mostly inaccessible to the miners. Review of literature on ASGM technology shows scarcity of information as majority of researches have primarily focused on the environmental and socio-economic impacts of the operations (Yalley, 2024). The very few developed technologies have not been sustainable due to implementation challenges (Yalley, 2024). Furthermore, formulated policies and regulations in attempts to formalize the operations have paid little attention to the technological needs of the sector.

Prevalent among such technological and knowledge gaps is the use of inappropriate mining methods for mining the various deposit types. Bansah, Yalley, & Dumakor-Dupey (2016) concluded that the benefits from ASGM have been annulled by the prevalent negative environmental and safety impacts which result from the use of inappropriate mining methods. Various studies echoed the need for the development and adoption of innovative and safe ASGM methods to ensure sustainability (Kuma & Yendaw, 2010; Dumakor-Dupey & Bansah, 2017; Mushiri, Jirivengwa, & Mbohwa, 2017). Mining method can be defined as the systematic approach to liberate the mineable ore from the earth's crust (Yalley, 2024). Mining method selection is the process of matching the characteristics of an orebody to the attributes of a mining method (Guray et al., 2003). The choice of a suitable mining method for a particular deposit type is critical to the economics, safety and productivity of the mine. Inappropriate choice or use of a mining method for a particular ore deposit results in ground failures, environmental degradation, safety and health hazards and low ore recovery rates (Guray et al., 2003; Ataei et al., 2008; Liu, Dong, & Dong, 2010; Bogdanovic, Nikolic, & Ilic, 2012; Gupta & Kumar, 2012; Ye & Liu, 2012; Shariati, Yazdani-Chamzini, & Bashari, 2013; Dehghani, Siami, & Haghi, 2017; Popovic, Dordevic, & Milanovic, 2019).

Whereas several mining methods have been developed for LSGM operations, with ASGM operations, mining method development, selection and its implications on the safety, economic and environmental sustainability of the operations have been given little attention (Yalley, 2024). Moreover, mining engineers and allied professionals employed in LSGM operations design and implement mining methods to suit the deposit characteristics. In contrast, many ASGM operations lack access to such expertise, hindering the adoption of suitable mining methods to ensure sustainable mining operations. Review of literature showed that only 2 studies, Salati, Mireku-Gyimah, & Eshun (2016) and Rupprecht (2017) have proposed mining methods for ASGM. Salati, Mireku-Gyimah, & Eshun (2016) proposed mining methods for ASGM operations in Nigeria, whereas Rupprecht (2017) proposed Bench mining method utilizing manual labour and mechanical equipment as an ideal ASGM method for in Central Africa.

In Salati, Mireku-Gyimah, & Eshun (2016) work, it was seen that all the underground mining methods proposed focused on development sequence without consideration given to the stoping technologies to be employed. Moreover, there were no considerations given to artisanal operations or manual operations as the proposed design parameters, schedules of operations and the equipment selection depicted only mechanized operations. In addition, the proposed equipment costs of $ 996 222.00 and $392 912.00 for the surface and underground operations are too much of a cost for ASGM operations to afford. This observation calls into question the authors' comprehension of the ASGM sector's operational dynamics. Whereas Salati, Mireku-Gyimah, & Eshun (2016) study looks good on paper, in practice it will be difficult for the miners to adopt. It is not surprising that no records were given about the implementation of the mining methods on any ASGM site. In Rupprecht (2017) study, the nature of the deposit and country rock that is applicable to this mining method was not clearly stated. There was no mention of the nature of the deposit appropriate for this mining method. In addition, the applicable depth of occurrence of the orebody was not stated, rather an information was given that the hard rock deposits in Central Africa usually occur around 20 m deep and beyond which is not economically viable for this method considering the quantity of waste materials to be stripped. Rupprecht (2017) explained that the implementation of the proposed mining method failed due to the lack of commitment from the mine owner and the miners. In the first instance, because the mine lacked the technical expertise to produce the mine designs and plans, there was the need to introduce a technical team to do that. However, there was reluctance from the mine owner to pay for the designs and implementation of the designs. Moreover, the workers sneaked to mine at night during the periods when there was the need to halt production temporarily to give room for the new designs to be implemented.

To address the gaps identified, this study is focused on developing safe and sustainable mining methods for ASGM operations exploiting alluvial or colluvial with hard rock potentials. Considerations were given to both artisanal operations and small-scale operations in terms of the designed mining methods, equipment and labour selection to ensure easy implementation. Moreover, both stoping and development techniques have been well represented in the methods. These deposit types were chosen for the study due to their prevalent nature.

2. Description of the Deposit Types

It is important for geology to lead mining for sustainable mining operations. To promote sustainable mining, a detailed exploration programme is required to determine the viability of a mining project. If that is not done, the miners will operate in a "trial and error" mode, thereby fostering deforestation and land degradation. This is because the "trial and error" form of mining usually does not yield enough revenue for the miners to use some for reclamation and revegetation. As such, this study emphasizes the need for acquiring geological information before implementation of the developed mining method. Thus, the geological features of the deposit types considered appropriate for the Bench Pit-Underground Mining (BPUM) have been explained in the sections below.

2.1. Alluvial Deposits

Alluvial gold occurs as gravels of streams, flats, and old valleys, on terraces and in beach gravels and sand. These are formed when primary vein and lode-type deposits are subjected to multiple cycles of erosion and deposition (Dzigbodi-Adjimah & Arhin, 1993; Dzigbodi-Adjimah & Asamoah, 2010; Alidu, 2017). Alidu (2017) explained that alluvial gold deposits in Ghana are mostly concentrated in the basal gravels overlying the weathered Birimian systems. The thickness of the gravels range between 1 m to 6 m and are rounded in shape with barren silt and clay as the overburden (Alidu, 2017).

2.2. Colluvial Deposits

Colluvial deposits are defined based on the process of formation, the material characteristics and position of the deposit on the landscape (Zádorová & Penížek, 2018; Pavlů et al., 2023). Zádorová & Penížek, (2018) explained that although the term colluvial deposits is a basic terminology in geosciences, the definition varies across different countries and scientific disciplines. Moreover, the concept of colluvial deposits coincides with the concept of alluvial deposits, thus presenting a challenge of similar ambiguity in definitions. Alluvial deposits are sedimentary deposits that have been transported by water whereas colluvial deposits are sedimentary deposits that have been transported by wind (Zádorová & Penížek, 2018). Colluvial deposits contain gravels which are angular in shape. Fuchs & Lang (2009) explained that colluvial sediments can be distinguished from alluvial sediments in the sense that colluvial sediments are obtained from spatially diffuse processes whereas alluvial sediments are obtained from spatially confined channels. In practice, it is often difficult to distinguish between alluvial deposits and colluvial deposits in the field (Lang, 2003). Thus, the reason why some geoscientists generally classify both alluvial deposits and colluvial deposits as alluvial deposits.

2.3. Hard Rock Deposits

This type of deposit is associated with gold bearing quartz which cuts sharply through the country rocks Alidu (2017). The mineralized quartz veins are identifiable by the medium to dark grey colour. The widths of the quartz veins range from a few millimeters to 2 metres, with a depth of about 500 m or more (Alidu, 2017). The veins may occur as extrusive rocks appearing as outcrops or as intrusive rocks which sometimes nip downwards and disappear beyond the reach of the SSGMrs (Alidu, 2017).

3. Materials and Methods Used

The materials and methods used in this study include field visits to 3 registered ASGM sites in Prestea and Asankrangwa in Ghana to ascertain the mining methods being used and the challenges they are encountering with the methods. The design parameters outlined in the mining laws and regulations of Ghana (Minerals & Mining Act 2006 (Act 703) and Health, Safety & Technical Regulations 2012 (L. I. 2182)) were used as guidelines for the development of the mining methods. Also, development of the mining methods, were based on the deposit characteristics suitable for Surface mining methods and the deposit characteristics suitable for Underground mining methods as outlined in Bullivant (1987). The development and design of the mining methods was done using Surpac 6.6.2 software and design tools in Microsoft PowerPoint.

3.1. Design Parameters from Mining Laws and Regulations

The Mining Laws and Regulations form the basic guidelines for carrying out sustainable mining operations. In this study, the Minerals & Mining Act 2006 (Act 703) and the Minerals and Mining (Minerals and Mining. Health, Safety and Technical Regulations, 2012) (L.I. 2182) of Ghana have been used as the baseline guidance for the development of the mining methods. However, because the developed methods are generic and do not depend on any ASGM site specific geological features, the methods are applicable to any other country which have alluvial or colluvial deposits with hard rock potentials. The methods could therefore be applicable to the ASGM sites by adopting the country specific minerals and mining laws as guidelines. **Table 1** below explains the important design parameters to be considered in the mine designs as indicated in the mining laws and regulations.

3.2. Design Parameters Based on Deposit Types and Characteristics

In conceptualizing the development of the mining methods, this study considered the deposit characteristics suitable for Surface mining methods and for Underground mining methods as explained in Bullivant (1987). Therefore, the study

Table 1. Mine design parameters as guidelines from the mining laws and regulations.

No	Design Parameter	Requirements
1	Licence duration	5 years subject to renewal for any further period deemed appropriate.
2	Concession size	From 5 acres to 25.2 acres.
3	Mining method	Any effective and efficient method.
4	Explosives usage	Only with written permission of the Minister upon recommendation from the Minerals Commission (MINCOM).
5	Mercury usage	Only with the written permission of the Chief Inspector of Mines (CIM) and with the use of a retort.
6	Blasting operations	Blasting schedule to be prepared and shared with the Inspectorate Division of Minerals Commission (IDMC).
7	Operating permit	Mining can only take place after the issuance of an Operating permit by the CIM. Operating plan to be submitted for the issuance of an operating permit.
8	Operating plan	Plan showing concession boundaries, mode of operations and rehabilitation plan.
9	Mechanized mining pit slopes	Working face slope equal to the angle of repose. Working face vertical height not more than 1.5 m beyond maximum reach of equipment. No undercutting of working surface. Benches and pit wall slopes less than the angle of repose.
10	Manual mining pit slopes	Working face slope equal to the angle of repose. Vertical height of working face not more than 3 m. No undercutting of working surface. Benches and pit wall slopes less than the angle of repose.
11	Rehabilitation and revegetation	Rehabilitation and revegetation to be done 1 month after mining. Rehabilitation certificate to be issued by the CIM after inspecting the reclamation project.
12	Outlets for underground small-scale mines	Underground mines should have 2 outlets that communicate to the orebody. Properly constructed ladderway in shafts or any approved mechanical hoisting means. Hemp rope not used as hoisting means to enter or leave an underground working except in early stages of development and depth of underground working is not more than 10 m.
13	Support for unsafe grounds	Unsafe grounds to be supported, filled or kept safe. Ore left as supports can only be mined with an approval from the CIM.
14	Mine drainage	Stagnant water and pools of water to be drained off. No fuel-powered water pump or equipment to be used underground except with written permission from the CIM.
15	Mine ventilation	Adequate ventilation provisions to all working areas. Persons not to work or enter areas of inadequate ventilation, excessive toxic gas, fumes, dust or temperatures. CIM will prescribe the minimum air quality.

Sources. Minerals and Mining Act 2006 (Act 703), Minerals & Mining (Health, Safety and Technical Regulations, 2012) (L.I. 2182).

employed the principle outlined in Bullivant (1987) as basis for characterizing the deposit types. Bullivant (1987) deposit classification was done generally for all deposit types. **Figure 1** and **Table 2** show Bullivant (1987) characterization of deposit attributes suitable for Surface mining methods and Underground mining methods respectively.

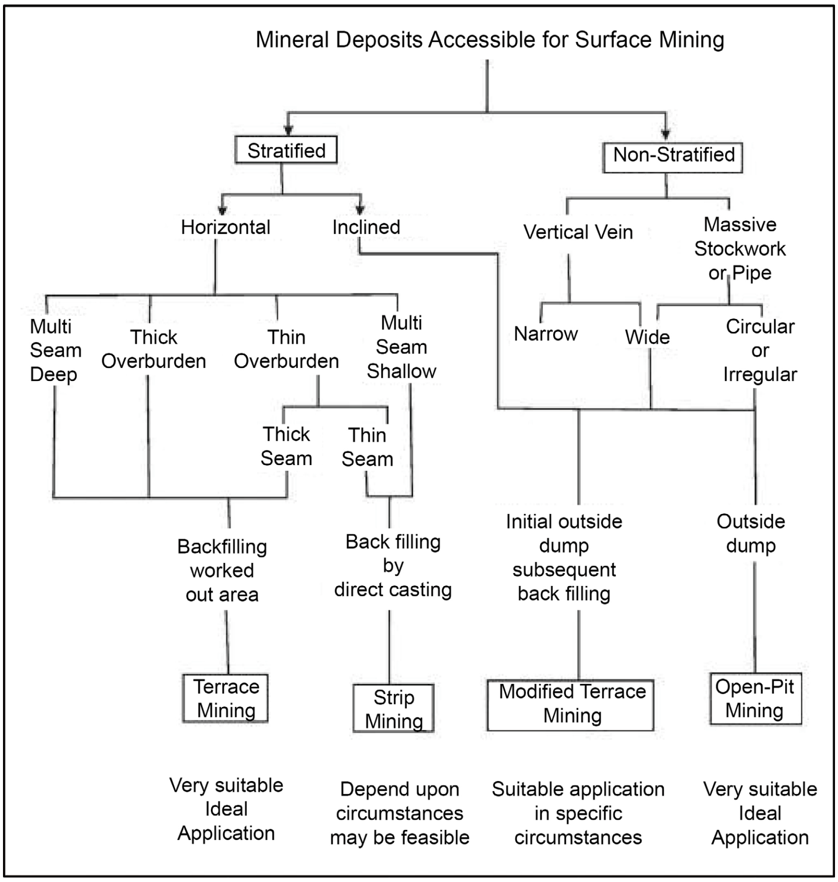

Figure 1. Ore Deposit Characteristics Suitable for Surface Mining Methods (Source: Bullivant, 1987)

Table 2. Mine Design Parameters as Guidelines from the Mining Laws and Regulations. (Source: Bullivant, 1987).

Underground Methods	Unsupported				Supported			Caving	
Factor	**Room and Pillar**	**Stope and Pillar**	**Shrinkage Stoping**	**Sublevel Stoping**	**Cut and Fill Stoping**	**Square Set Stoping**	**Longwall Stoping**	**Sublevel Stoping**	**Block Caving**
Ore strength	Week/ Moderate	Moderate/ Strong	Strong	Moderate/ Strong	Moderate/ Strong	Weak	Any	Moderate/ Strong	Weak/ Moderate
Rock strength	Moderate/ Strong	Moderate/ Strong	Strong	Fairly Strong	Weak	Weak	Weak/ Moderate	Weak	Weak/ Moderate
Deposit shape	Tabular	Tabular/ Lenticular	Tabular/ Lenticular	Tabular/ Lenticular	Tabular/ Irregular	Any	Tabular	Tabular/ Massive	Massive/ Thick
Deposit dip	Low/Flat	Low/ Moderate	Fairly steep	Fairly Steep	Fairly Steep	Any	Low/Flat	Fairly Steep	Fairly Steep
Deposit size	Large/Thin	Any	Thin/ Moderate	Thick/ Moderate	Thin/ Moderate	Unusually Small	Thin/ Wide	Large/ Thick	Very Thick
Ore grade	Moderate	Low/ Moderate	Fairly High	Moderate	Fairly high	High	Moderate	Moderate	Low
Ore uniformity	Uniform	Variable	Uniform	Uniform	Variable	Variable	Uniform	Moderate	Uniform
Depth	Shallow/ Moderate	Shallow/ Moderate	Shallow/ Moderate	Moderate	Moderate/ Deep	Deep	Moderate/ Deep	Moderate	Moderate

3.3. Information about Study Sites

A total of 3 ASGM sites were used in this study. Two (2) of the selected sites are located in Prestea whereas 1 site is located in Asankrangwa all in the Western Region of Ghana. The Prestea town and Asankragwa town were chosen for the study due to the dominance of ASGM operations and the long history of ASGM operations. Moreover, the selected sites had typical examples of the deposit types referred to in this study.

Prestea is bounded by latitudes 5˚26'14.352''N and longitudes 2˚8'24.4104''W. The town is located about 200 km from the capital Accra and 50 km from the coast of the Gulf of Guinea. It is accessible by road to Accra through a 6-hour drive through Takoradi, the Harbor city. Prestea has a tropical wet and dry (savanna) climate. The district's yearly temperature is 27.44˚C (81.39˚F) and it is -1.42% lower than Ghana's averages. Gold deposits in Prestea are made up of quartz veins and the disseminated sulphide. According to Dzigbodi-Adjimah & Asamoah, (2010), the quartz vein orebodies are generally of higher gold grades and lie within a graphitic gouge in the fissure zones whereas the disseminated sulphide are mostly located in sheared or crushed rocks near the fissure zones.

Asankrangwa is the capital town of the Amenfi West Municipal of Ghana. The geology of the Asankrangwa Belt consists of the strongly deformed Birimian metasediments, with minor granitic intrusions and mafic igneous rocks. The Asankrangwa gold belt is located within the Kumasi basin which is dominated by paleoproterozoic metasedimentary and metavolcanic rocks. The belt is 200 km long and 20 km wide and has gold deposits and occurrences contained in it (Galiano Gold Report, 2024).

4. Results and Discussions

4.1. Results from the Field Studies

The field studies conducted at 2 ASGM sites in Prestea and 1 site at Asankrangwa showed that the miners lacked knowledge about the best mining methods for their operations. At Asankrangwa, operations had halted because the pit had reached an unstable state. There were some few benches put in at the upper side of the pit whereas about 30 m of the walls to the bottom of the pit had no benches. The benches that were put in were too steep, about 80˚ making them unstable. At the site, materials kept reeling down showing evidence of unstable pit walls. The 2 mines at Prestea had similar issues even though they were operating. There were evidence of materials reeling down even as they were mining. **Figures 2(a)-(c)** show images of the unstable pits of the mine in Asankrangwa and the 2 mines in Prestea.

4.2. Development of Mining Methods for ASGM Operations with Alluvial and Hard Rock Potentials

In this study, the Bench pit-underground mining (BPUM) method is developed

(a)

(b)

(c)

Figure 2. Images of the Unstable P at the (a) Prestea site 1 (b) Asankrangwa site (c) Prestea site 2.

and designed to be used for ASGM operations with either alluvial or colluvial deposits and hard rock potentials. The mining method, design parameters, mine designs, schedule of operations, equipment and labour selection have been given in the sections below.

4.2.1. Bench Pit-Underground Mining Method (BPUM)

The developed BPUM method takes into consideration the characteristics of the deposit type. For such deposits, the topmost part consists of loose unconsolidated materials with gravels. Below the unconsolidated portion lies the transition materials which has a blend of oxide materials and rock materials. Below the transition materials lies the hard bedrocks. The depth of occurrence of each of the layers of materials may differ from one geological terrain to another. Such deposits extend vertically or deeply into the earth crust but are limited in terms of lateral extension. The bench pit-underground mining method considers the upper portions of the deposit to be mined by opening up pits to the widest and deepest economic and safety limits. The lower portions can then be mined by underground techniques. A series of benches are created to ensure pit wall stability throughout the mine life. This study considers different designs for artisanal/manual operations and mechanized operations.

4.2.2. Design Parameters

This mining method takes into account the extent of the mineable ore zones in the design and allocation of surface infrastructure. It is recommended that surface structures and dumps occupy a maximum of 20% of the total concession area and in the barren areas or low ore zones. However, variations could be made to satisfy the concession specifications and specifications in the country's mining laws. For flexibility and cost reduction, it is recommended that the miners employ the use of movable infrastructure such as container offices instead of fixed structures especially in cases of short mine life. These structures could be transported and re-used in other future acquired concessions.

4.2.3. Artisanal BPUM

The design parameters for artisanal BPUM have been given below.

- Bench slope angle ≤ Angle of repose.
- Pit slope angle ≤ Angle of repose.
- Bench height = 1.0 m.
- Bench width = 1.0 m.
- Haul road width = 1.5 m.
- In-pit haul road design = Series of steps at the stable side of the pit.
- Pit size = Depend on the deposit size, production targets, cut-off grade, stripping and ground stability conditions.
- Overall pit depth = Dependent on the break-even stripping ratios.
- Haul road gradient = 8^0 or 8%.
- Shaft width = 1.5 m.
- Level access height = 1.5 m.
- Level access width = 1.0 m.
- Crosscut height = 1.5 m.
- Crosscut width = 1.0 m.
- Ore drives height = 1.5 m.
- Ore drives width = 1.0 m.
- Maximum stope height = 3 m.

- Inter-level distances = 10 m.
- Distances between shafts = 30 m.

4.2.4. Mechanized BPUM

The design parameters for mechanized BPUM have been given below.

- Bench slope angle ≤ Angle of repose.
- Pit slope angle ≤ Angle of repose.
- Bench height = 3 m.
- Bench width = 1.5 m.
- Bench width = Dependent on the width of the widest equipment employed.
- Haul road width (mechanized operations) = Width of the widest equipment employed.
- Ramp width = Width of the widest equipment employed.
- Pit sizes and number of pits = Depend on the deposit size, production targets, cut-off grade, stripping and ground stability conditions.
- Overall pit depth = Dependent on the break-even stripping ratios.
- Haul road gradient = 8˚ or 8%.
- Shaft width = 2.5 m.
- Level access height = 2.5 m.
- Level access width = 2.0 m.
- Crosscut height = 2.5 m.
- Crosscut width = 2.0 m.
- Ore drives height = 2.0 m.
- Ore drives width = 1.0 m.
- Maximum stope height = 3 m.
- Inter-level distances = 10 m.
- Distances between shafts = 30 m.

4.2.5. Other Design Considerations

Other design considerations to be made include.

- Ditches and sumps should be designed to dewater the pits and underground.
- Escape routes should be provided at vantage points underground.
- Water from the sumps should be pumped into the settling ponds for reuse.
- Surface infrastructure includes mine offices, mechanical workshops, electrical substation/generator set, processing plant, settling ponds, ore pads, the overburden/waste dumps and topsoil stockpile.

Table 3 below summarizes the facilities required in the Mine offices.

4.3. Scheduling of Operations

For easy mining of the ore deposit, the work to be done to obtain the ore has been scheduled into surface development, surface mining, underground development, underground stoping, underground backfill, surface reclamation and revegetation.

Table 3. Summary the facilities required in the mine offices.

Surface Infrastructure	Facilities Required
Mine offices	Offices for managers, supervisors, engineers, Human resources/Administration, Accounts offices Meeting room Clinic or first aid room Dining room/kitchen Changeroom Toilets and Bathrooms
Mechanical Workshop	Mechanical workshop Mechanical/Electrical office Stores

4.3.1. Surface Development

This work phase involves clearing of the land area for surface infrastructure, haul roads construction, construction of the surface infrastructure, clearing of areas to be used as dumps and stockpiles, installation of fixed equipment, demarcation of the mining area. It is important that the surface infrastructure are positioned away from the ore zone in order to avoid relocation of the surface infrastructure in future. As such the land area being occupied by the ore block should be demarcated first through geological exploration then the surface infrastructure area will be demarcated. All surface structures should be located within the concession boundaries. The schedule of these operations will begin with clearing of the vegetation on the area earmarked for the surface infrastructure and the haul roads. This will then be followed by the construction of the haul roads, construction of the mine offices and maintenance workshop, electrical substation setup, ore pad construction, setup of the processing plant and the dam and settling ponds. The last work to be done will be the construction of the topsoil stockpile and the overburden/waste pad.

4.3.2. Surface Mining

Work within this phase will involve exposure of the ore for mining and transportation of the ore to the processing plant. This will begin with clearing of the vegetation, removal of topsoil for stockpiling, overburden removal, construction of the ramps and mining of the ore in a series of benches. The depth and width of the pit will depend upon the size of the deposit, cut-off grade and ground stability. The waste removed will be transported to an out-of-pit waste dump whereas the ore will be transported to the ore pad for processing.

4.3.3. Underground Development

Development work in the underground mine will begin with sinking of a shafts (one at the pit bottom and the other from surface). Then the level accesses, crosscuts and ore drives will be developed. Other underground structures such as waste and ore stockpiles will be created in the level accesses or ore drives. Also, there will be the development of electrical cuddies, toilet facilities, canteens, escapeways at vantage points. There will also be the development of sumps at vantage levels and at the bottom of the shaft and the boring of drains/ditches to direct the water into the sumps to be pumped out of the mine.

4.3.4. Underground Stoping

The stoping technology to be used to mine the ore deposit depend upon the size of the orebody. The cut stoping technique is proposed to be used for mining the orebodies. In the cut stoping, stoping is done from the crosscuts. Main level accesses are created with an interlevel distance of 10 m apart. Mining of the ore begins with the cutting of the first stope just at the entrance of the crosscut. Subsequent stopes will then be mined concurrently at the southern and northern side of the level access. The maximum height of the stope is proposed to be 3 m. Stoping is done in an advancing manner that is from the main entrance to the outer faces of the stope. Once stoping is complete on a level, the level is backfilled, backslashing is done and the same level serves as the floor to be used to mine the next level. An access is created from the main level access to hit the ore on the next level. The ore is mined in the same manner and backfilled. The same procedure is repeated until 3 cuts have been mined and backfilled. A 1 m height sill pillar is then left to serve as a support. Stoping can be done on several levels at a time to ensure that miners have more faces to work.

4.3.5. Underground Backfill and Mine Closure

The works to be done during the mine closure phase will be to ensure that after mining of the orebody, the underground excavation are well backfilled and rehabilitated in a manner to ensure that the grounds both within the underground excavations and the grounds on the surface of the earth remain stable. It is important to ensure that after the mining operations, there are no possibilities of ground deformation, caving and subsidence and that the entire concession area is kept safe. As such all underground water will be pumped out and all mined out areas will be backfilled and well supported. Backfill materials that could be used include the waste materials, concrete and cemented hydrafill (tailings materials mixed with cement and piped underground). All weak zones and high stress areas will have to be supported adequately to prevent ground falls. Available support materials for such weak zones include steel meshes, shotcrete, rockbolts and cablebolts. The recommended materials for high-stress areas include cablebolts, rebar, steel arches and steel supports.

4.3.6. Surface Backfill and Revegetation

The work within this phase involves all the works to be done after the ore material has been fully exploited. It is important to ensure that after mining, the land is fully reclaimed and left in a useful state for the land owners. The sequence of work in this phase involves removal and transportation of all surface structures and equipment from the mine site. It is recommended that ASGMrs use movable structures instead of fixed structures especially in areas where the mine life is short. This will reduce the cost of erecting new structures on every mine site and also could be an added revenue where the structures could be sold after use. The next sequence of operations will be to treat all the water in the ponds and gather them into a single pond. Backfilling and revegetation of the empty settling ponds, dumps, haul roads and the office areas will be done next. The treated water in the dams could be used for irrigation, for fish farming or could be pumped into a reservoir for the community to use and the dam area backfilled and revegetated. It is important to note that after the mining, the entire land area should be well levelled and without any voids or pits left to collect water or become swampy and serve as death traps for the inhabitants.

5. Designs of the Mining Method

The designs of the mining methods have been shown in the images below. Figure 3 and Figure 4 are the plan and sectional views of the mechanized development of the BPUM method. Figure 5 and Figure 6 are the plan and sectional views of the manual/artisanal development of the BPUM method. Figure 7 is a stoping technique to be employed for the BPUM method.

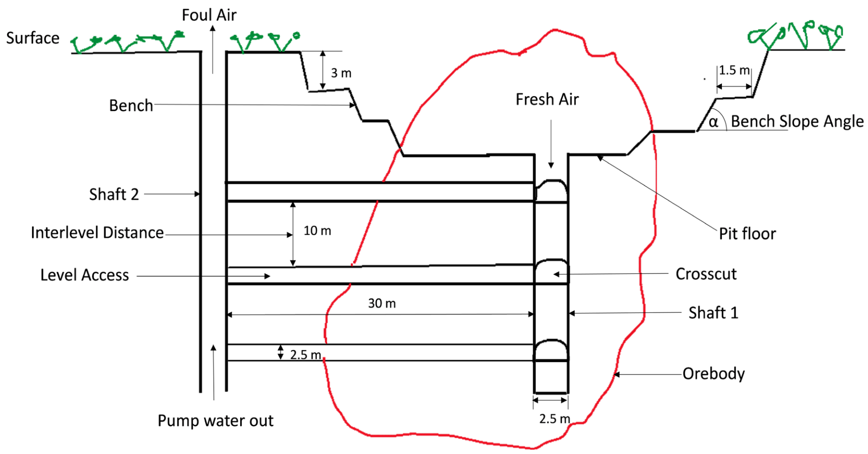

Figure 3. Sectional view of the mechanized development of the BPUM method.

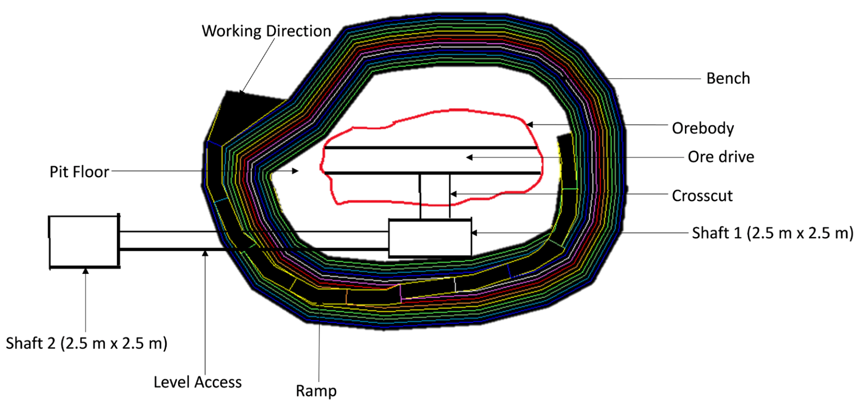

Figure 4. Plan view of the mechanized development of the BPUM method.

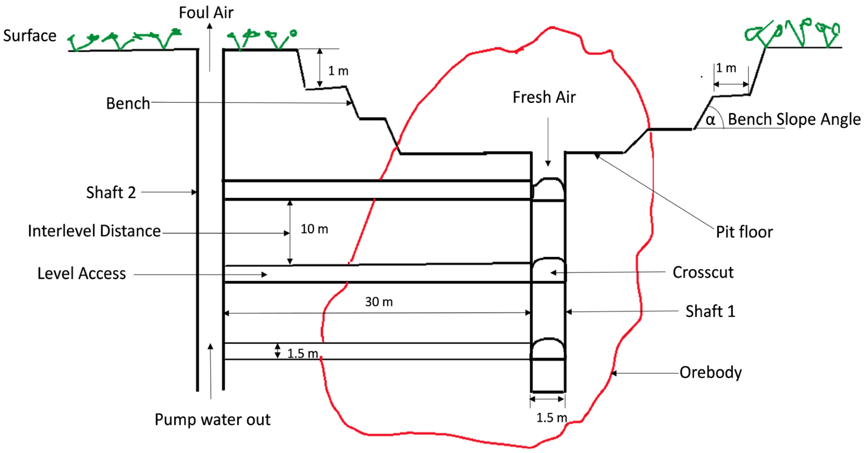

Figure 5. Sectional view of the manual development of the BPUM method.

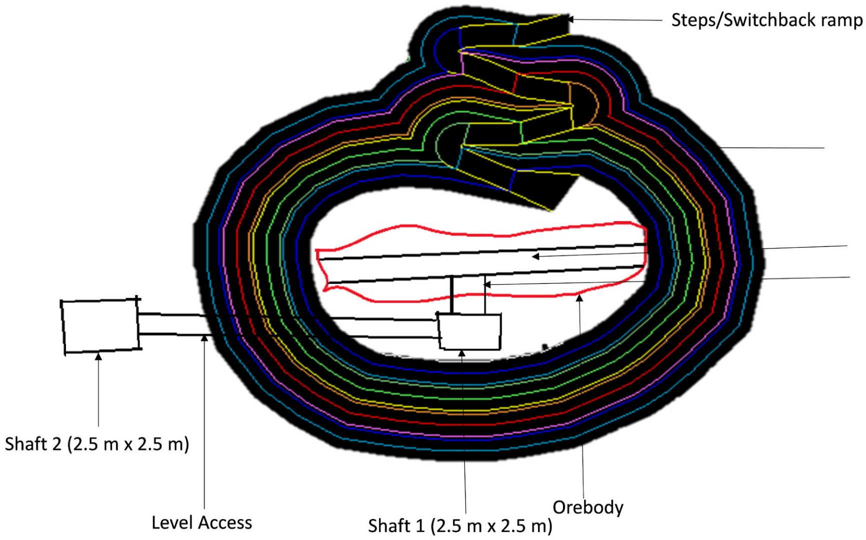

Figure 6. Plan view of the manual development of the BPUM method.

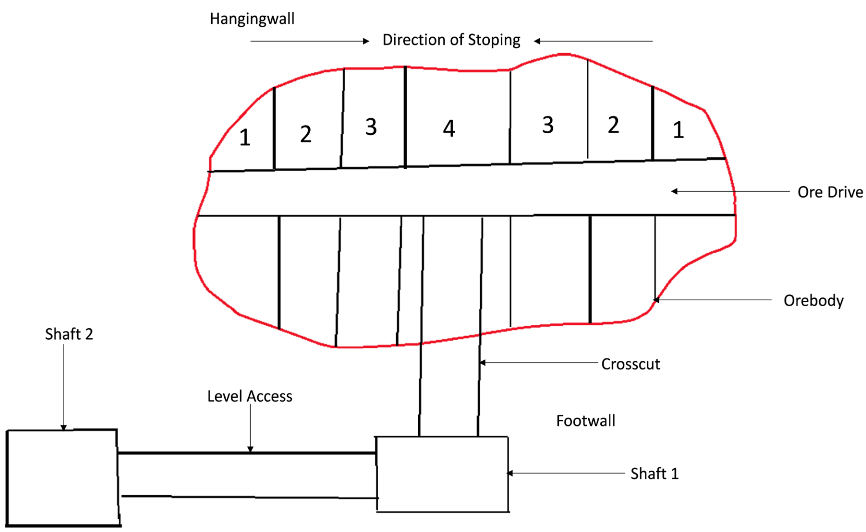

Figure 7. Plan view of the stoping technique to be employed for the BPUM method.

6. Equipment Selection

Equipment selection for BPUM will depend on the level of mechanization of the operations and whether equipment will be bought or rented for the operations. This study considered equipment selection for mechanized operations and manual operations. The operations will have to check the economic viability of hiring or purchasing equipment and use the best option. Table 4 and Table 5 give details of equipment required for surface and underground work respectively for mechanized Bench pit-underground mining. Table 6 and Table 7 give details of equipment required for surface and underground work respectively for manual BPUM.

Table 4. Equipment Required for the Mechanized Surface mining.

Item No	Equipment	Specifications
1	Excavator	Working radius – 11.3 m Digging depth – 7.5 m Bucket capacity – 3.5 m3 Width – 3.2 m
2	Dump Trucks	Capacity – 20 tonnes Width – 2.5 m Maximum speed – 50 km/hr
3	Dozer	Blade capacity – 1.99 m3 Blade width – 3.2 m Length – 4.3 m
4	Front-end-loader	Bucket capacity – 4.5 m3 Width – 2.5 m Length with bucket on ground – 8.8 m Reach at maximum lift and dump – 1.3 m
5	Grader	Overall length – 8.9 m Width – 2.5 m Blade width – 2.7 m
6	Dewatering pump	Pumping capacity – 538 litres (142 gallons) per minute Maximum head – 35 m Maximum pressure – 49.8 psi Suction discharge – 51 × 51 mm
7	Diesel generator	Rated capacity – 150 kvA standby; 50 Hz; 240/415 V; 0.8 PF Fuel tank capacity – 340 litres Fuel run hour – 9 hr (at 75 % load)
8	Water Truck	

Table 5. Equipment Required for the Mechanized Underground mining.

Item No	Equipment	Specifications
1	Jackhammer	Bore diameter: 34 mm Working pressure: 0.4 mpa Impact energy: 44 J Drill speed: ≥ 250 Mm/min
2	Jacklegs	Bore diameter: 34 mm Working pressure: 0.4 mpa Impact energy: 44 J Drill speed: ≥ 250 Mm/min
3	Alimak raise borers	Alimak raise borers
4	Slushers	Slushers
5	Ventilation fans	Voltage: 110 V Power: 24.4 W Speed: 2450 m/s
6	Water pumps	Rotating speed: 2875 r/min Pump head: 40 m Motor power: 9.2 kw Matching pipe diameter: 89 mm
7	Diesel generators	Rated capacity: 150 kvA standby; 50 Hz; 240/415; 0.8 PF Fuel tank capacity: 340 litres Fuel run hour: 9 hr (at 75 % load)
8	Compressors	Compressors

Table 6. Equipment required for the manual surface mining.

Item No	Equipment	Specifications
1	Pickaxes	
2	Shovels	
3	Head pans	
4	Dewatering pumps	Pumping capacity – 538 litres (142 gallons) per minute Maximum head – 35 m Maximum pressure – 49.8 psi Suction discharge – 51 × 51 mm
5	Diesel generator	Rated capacity – 150 kvA standby; 50 Hz; 240/415 V; 0.8 PFFuel tank capacity – 340 litres Fuel run hour – 9 hr (at 75 % load)

Table 7. Equipment required for the manual underground mining.

Item No	Equipment	Specification
1	Jackhammers	Bore diameter: 34 mm Working pressure: 0.4 mpa Impact energy: 44 J Drill speed: ≥ 250 Mm/min
2	Jacklegs	Bore diameter: 34 mm Working pressure: 0.4 mpa Impact energy: 44 J Drill speed: ≥ 250 Mm/min
3	Ventilation fans	Voltage: 110 V Power: 24.4 W Speed: 2450 m/s
4	Water pumps	Rotating speed: 2875 r/min Pump head: 40 m Motor power: 9.2 kw Matching pipe diameter: 89 mm
5	Diesel Generators	Rated capacity: 150 kvA standby; 50 Hz; 240/415; 0.8 PF Fuel tank capacity: 340 litres Fuel run hour: 9 hr (at 75% load)
6	Compressors	Compressors

7. Labour Requirement

The quantum of labour required for BPUM is dependent on the levels of mechanization and the size of the operation. Table 8 and Table 9 detail the basic labour required for mechanized operations and the labour required for manual operations respectively.

Table 8. Labour Requirement for Mechanized BPUM.

Item No	Designation	Employment Condition
1	General Manager	Full-time
2	Mining Engineer/Mine Manager	Full-time
3	Geologist	Full-time
4	Surveyor	Full-time
5	Metallurgist	Full-time
6	Mine operations supervisors	Full-time
7	Mechanical Foreman	Full-time
8	Electrical Foreman	Full-time

Continued

9	Environment and Safety Engineer	Full-time
10	Human Resources Officer/Community Relations Officer	Full-time
11	Finance Officer/Purchasing officer	Full-time
12	Plant workers	Full-time
13	Equipment operators	Full-time
14	Service crew/Pump attendants	Full-time
15	Mechanics	Full-time
16	Electricians	Full-time
17	Cleaners	Part-time

Table 9. Labour Requirement for Manual BPUM.

Item No	Designation	Employment Condition
1	General manager/Mining engineer	Full-time
2	Mine operations supervisor	Full-time
3	Metallurgist	Full-time
4	Geologist	Part-time
5	Surveyor	Part-time
6	Health, Environment and Safety Officer/ Community Relations Officer	Full-time
7	Human Resources officer/Finance officer/ Stores keeper and Purchasing officer	Full-time
8	Diggers/Loaders	Full-time
9	Carriers/Transporters	Full-time
10	Processing plant workers	Full-time
11	Electricians/Service crew	Full-time
12	Security officers	Full-time

8. Conclusions and Recommendations

ASGM is an important contributor to the development of many economies across the globe. The sector is known to produce over 20% of the global gold production, employ millions of people, provide indirect jobs for individuals, promote rural economic growth and provide revenues for governments. However, analysis of the ASGM operations indicates that the operations are associated with poor mining techniques and technology which have resulted in low production levels, negative environmental, safety, social and economic impacts. Prevalent amongst such challenges is the frequent fatalities that occur on the mine sites due to collapse of their pits and underground excavations. Whereas governments and other global institutions recognize the importance of this sector and the need to formalize it, it is observed that the formalization processes have given little attention to the technological needs of the sector. Moreover, there is still a gap in literature regarding sustainable mining methods for ASGM. The aim of this study is to fill the gap in literature, provide guidance for the less skilled ASGM miners and promote sustainability by developing mining methods for ASGM operations working on alluvial or colluvial deposits with hard rock potentials. The developed methods took into considerations manual/artisanal operations and mechanized operations.

The methods used for the study included field visits to 3 ASGM sites in Prestea and Asankragwa which exploit similar deposit types. Also, the design parameters proposed in this method took into account the standard design parameters in the Ghana mining laws. Results from the field studies indicated that the miners did not know the efficient and sustainable methods to exploit their deposit. The BPUM mining method was therefore developed as the best method to be used by the miners. The design parameters, schedule of operations, equipment and labour selection for both artisanal and mechanized operations were given. It is therefore recommended that ASGM operations exploiting such deposit types employ the BPUM mining method to ensure safety, sustainability and high productivity. The miners have the options to either hire or purchase their equipment. Also, for efficient implementation of the mining method on the sites, the study recommends that operations that cannot afford to employ permanent mining engineers and geoscientists should form cooperatives and hire these individuals to provide the needed services on their sites. As such, the payments of such professionals will be done by the groups. The developed mining method will ensure sustainability and could be adopted globally so far as the deposit types are alluvial or colluvial with hard rock potentials. To ascertain the cost benefits of this method, it will be important to implement this method on a selected mine site and compare it to existing methods used in the same site or a different site with similar deposits characteristics. Further studies could concentrate on the dynamics of the implementation of this method and report on it. These would be used as basis to improve the mining technique.

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Authors' Contribution

The 3 authors contributed to the conceptualization and the research design. Materials preparations data collection and analysis was conducted by Ms. Akuba Bezeba Yalley. The draft manuscript was written by Ms. Akuba Bezeba Yalley. It was then reviewed by Dr. Bright Oppong-Afum and Prof George Agyei. The final manuscript was approved by all the authors.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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