PROPOSED MINING AND PROCESSING METHODS FOR EFFECTIVE MANAGEMENT OF ARTISANAL AND SMALL-SCALE GOLD MINING IN NIGERIA

L. K. Salati[1],D. Mireku-Gyimah[2] and P. A. Eshun[2]

[1]Department of Mineral and Petroleum Resources Engineering, Kaduna Polytechnic, Kaduna, Nigeria

[2]Department of Mining Engineering, University of Mines and Technology, Tarkwa, Ghana

Abstract: The Artisanal and Small-scale Gold Mining (ASGM) sector in Nigeria is in a deplorable state characterised by the use of inadequate mining and processing methods and manual tools by the local miners,resulting in dire environmental consequences and huge loss to the national economy. To address thispoor state of ASGM, suitable surface and underground mining methods for the exploitation of different types of gold deposits in Nigeriahave been proposed in this study. Strip, terrace and shallow open pit mining methods are proposed for surface mining. The maximum allowable depth for the shallow open pit is fixed at 15 m, beyond which a gold deposit can be exploited by underground mining method to a depth of 50 m using adit or vertical shaft openings. For complete elimination of mercury use in ASGM, direct smelting and igoli processing methods are proposed. The estimated costs of equipment for the proposed surface mining, underground mining and processing methods are $ 996 222.00, $ 392 912.00 and $ 40 707.00 respectively. Waste management, flood control and reclamation measures are recommended for efficient operation, while manpower and equipment requirements are proposed for optimum performance and utilisation. Reporting templates are developed to guide the operators.

Keywords: Mining and processing methods; mining and processing equipment; semi-mechanised operation; waste management; manpower requirements.

1. Introduction

ASGM operators can carry out productive, safer and environmental compliant mining operations, if their activities are streamlined through the development of suitable mining and processing methods. Although open pit mining remains the ideal means of exploiting hard rock through the removal of overburden and creation of benches (Bullivant, 1987), the high technical requirements of this method have restricted its effective use to only certified ASGM companies with adequate equipment and personnel. Strip mining, which involves the removal of the top soil or rock (overburden) above the ore layer to remove the exposed mineral,can be completed in rectangular blocks in plain view called pits or strips (Schissler, 2006) by the local operators, and this exposes the gold bearing gravels to stripping. According to Mireku-Gyimah (1995), a typical alluvial deposit with a vertical cross section made up of vegetation, topsoil (0.2 m), gold-bearing gravels (1.2 m) and the underlying bedrock (0.3 m) respectively can be mined using both manual and mechanised mining methods. Priester*et al*. (2010) strongly advocate support for the mechanisation of ASGM operations with a view to standardising them and boosting their productivity. Although the exploitation of narrow reefs and deep veins requires special underground rock cutting technology and technique (Pickering *et al*, 2006), ASGM operators are often driven by lack of financial and technical means to run improvised underground workings (Amankwah and Anim-Sackey, 2003; Eshun, 2005).

The contribution of ASGM through the release of gaseous mercury into the environment is immense due to poor and indiscriminate disposal of amalgamation residues by the local miners. As part of the interventions to reduce mercury-induced environmental pollutions in ASGM alternative gold processing methods which include winnowing, agglomeration, smelting and leaching processes such as Igoli, Haber and cyanidation (Amaknwah*et al.*, 2010) can be prescribed for local operators. Also, cheaper and safer extraction methods proposed by recent studies for ASGM operators include direct smelting and borax (Abbey *et al*., 2014; Appel and Jonsson, 2010). Direct smelting potentially replaces amalgamation and retorting, while borax (sodium borate) reduces the melting point of gold during the smelting process.

SinceASGM involves manual exploitation of hard rocks and alluvial deposits without any prior exploration, the sector is poorly managed and thus remains underdevelopedover the years. The management of ASGM in Nigeria is characterised by manual labour, fetish cultural practices, unregulated and unlicensed activities by both local miners and aliens, use of mercury, child labour, chaos and crime-laden mining scenes and serious environmental degradation (Azubike, 2011; Abdulsalam, 2012; Basharu, 2012; Mallo, 2012). To address the highlighted problems, this paper, therefore, proposes suitable mining and processing methods for ASGM operators in Nigeria to ensure effective management of their operations.

2. Proposed Mining and Processing Methods for ASGM in Nigeria

2.1 Mining Methods

The proposed mining methods for the ASGM operators include strip, terrace and shallow open pit mining methods for alluvial (elluvial or colluvial), weathered (gold lode, phyllitic, quartzitic and lateritic) materials, and auriferous lodes and quartz vein deposits respectively. Small underground adit or vertical shaft opening method is proposed for auriferous lodes and quartz veins in hilly terrains or flat plains beneath the 15 m depth in shallow open pit method. Table 1 shows template of the proposed mining methods for ASGM operators in Nigeria.

Table 1 Mining Method Selection Template for ASGM Operators in Nigeria

S/N	Type of Deposit	Proposed Mining Method
1.	Alluvial / elluvial / colluvial deposits	Strip mining
2.	Weathered gold lodes, phyllitic, quartzitic and lateritic materials	Terrace mining
3.	Auriferous lodes and quartz veins with depth ≤ 15 m	Shallow open pit mining
4.	Auriferous lode and quartz vein deposits in hilly terrains or flat plains with depth > 15 m < 50 m	Underground mining (adit or vertical shaft opening)

2.1.1 Strip Mining Method

Strip mining method is proposed for the ASGM operators to exploit alluvial, colluvial and elluvial deposits. A typical alluvial deposit with a vertical cross section consisting of vegetation, overburden, gold-bearing gravel and the underlying bedrock can be mined using the proposed method (Mireku-Gyimah, 1995).

For a minimum licensed area measuring 20 234 m^2 (5 acres) specified by the Minerals and Mining Act of 2007 for ASM operations, the proposed layout and mining sequence are shown in Fig. 1. The overburden area occupies 2 808 m^2; the access road and haulage road occupy a total area measuring 2 184 m^2; and the mine office and workshop, washing plant, washed gravel stockpile and settling pond cover a total area measuring 6 864 m^2. After these areas have been marked out, the area left is then divided into six panels of approximate size of 53 m x 26 m each. Fig. 1 shows the proposed strip mining method. The clearing of vegetation precedes strip mining which commences from one end towards the other. The mining of the panels as illustrated in Fig. 1 is done in sequence from West to East (i.e. Panel 1 to Panel 6) and North to South within the panel as illustrated in Panel 4.

From Panel 1, the overburden is removed and dumped at the overburden stockpile area for future use in reclamation. The gold bearing gravel from Panel 1 is also removed, washed and the waste taken back into Panel 1. The overburden from Panel 2 is then used to cover the gravel in Panel 1. The gravel in Panel 2 is also removed, washed and returned, while the overburden in Panel 3 is removed and put on top of the washed gravel in Panel 2. There is now access to the gold bearing gravel in Panel 3 which is then removed, washed and the waste returned. The overburden from Panel 4 is then used to cover the washed gravel in Panel 3. This process continues until the gravel in Panel 6 which has been removed, washed and taken back to fill the panel is then covered with the overburden from Panel 1. Hence, the gold bearing gravel excavated from each panel is hauled to the sluice box through the access road, washed and returned before being covered with the overburden from the next panel.

Land reclamation is enhanced through the sequence of mining the panels.From Fig. 1, Panel 1 has been mined, backfilled and re-vegetated; Panel 2 has been backfilled and is being prepared for re-vegetation; Panel 3 has been mined out and is yet to be backfilled; Panel 4 is currently being mined; Panel 5 has its overburden currently being removed; and vegetation is being cleared from Panel 6.

Strip mining effectively reclaims the mined-out-areas through systematic stripping thereby making the land ready for re-vegetation. The method reduces environmental degradation and sustains the original land use for farming. To ensure slope stability in the reclamation process, all the washed gravels must be brought back to fill up the pit to further stabilise the pit wall.

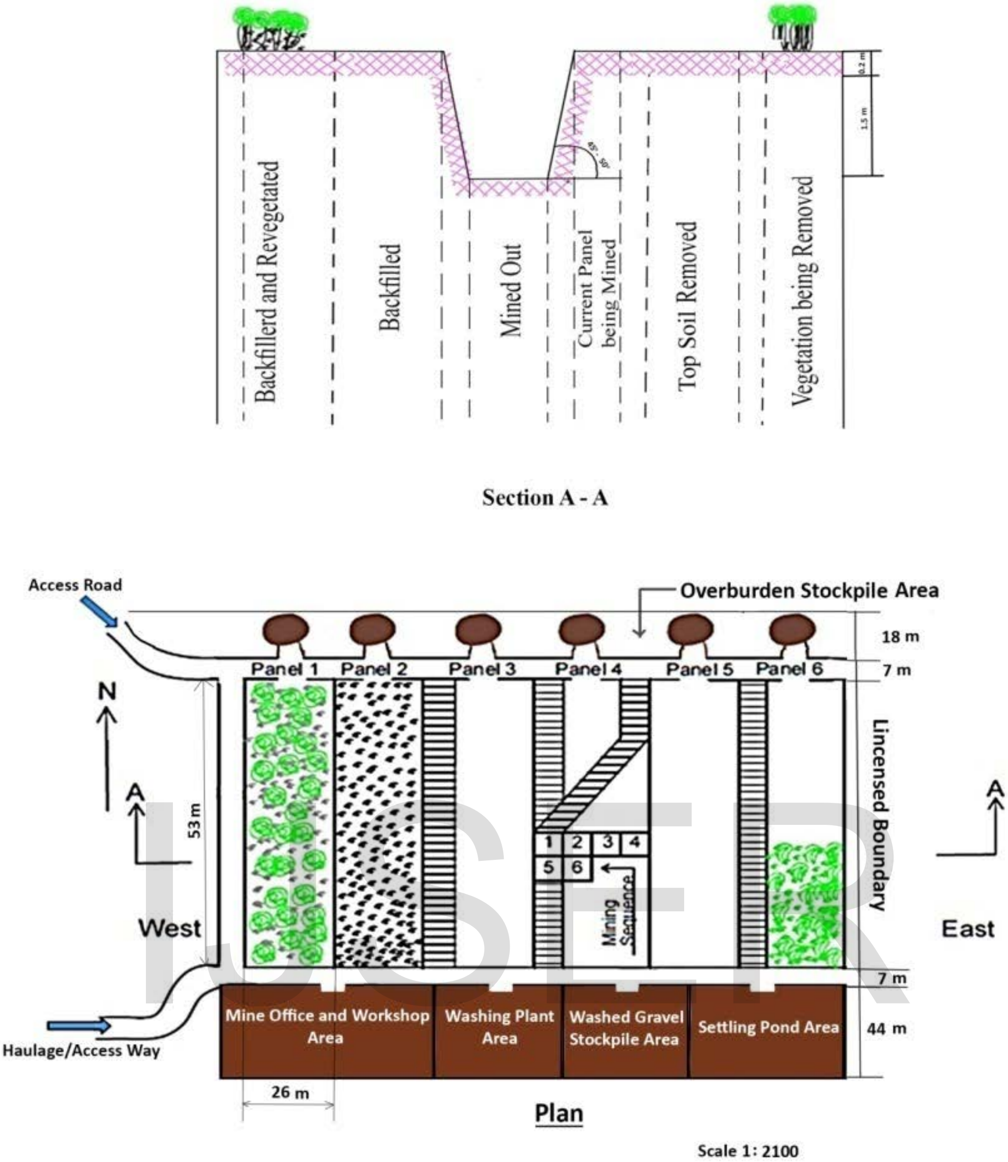

Fig.1 Proposed Strip Mining Method for Alluvial Deposits (Modified after Mireku-Gyimah, 1995)

2.1.2 Terrace Mining Method

A special strip mining method termed 'terrace mining' is proposed for the ASGM operators as a method of mining weathered gold lode, phyllitic, quartzitic and lateritic materials. Such deposits can be mined in terraces or benches along the hillside. To avoid destroying the road, distance from the mining area to the road side should be at least 100m(Eshun and Mireku-Gyimah, 2002). The terraces are then divided into convenient sizes to allow miners easy passage, each block consisting of a bench and a slope ranging between 30° - 35° to prevent wall collapse.

Overburden is first removed and stockpiled to a safe place to be used for future reclamation. Removal of rock materials starts from the hill top and proceeds to the bottom direction, while each block is mined from one end to the other, taking care to create adequate benches beneath each mined block to ensure slope stability and prevent erosion. Creation of access road is also encouraged between the slopes to connect them to the benches. Fig. 2 shows the plan and section views of the proposed terrace mining method for the exploitation of weathered gold lodes, phyllitic, quartzitic and lateritic materials along hilly areas. Thus, this method is considered suitable for the mining of weathered materials that have been exposed for many years but which are not primary deposits (Mireku-Gyimah, 1995).

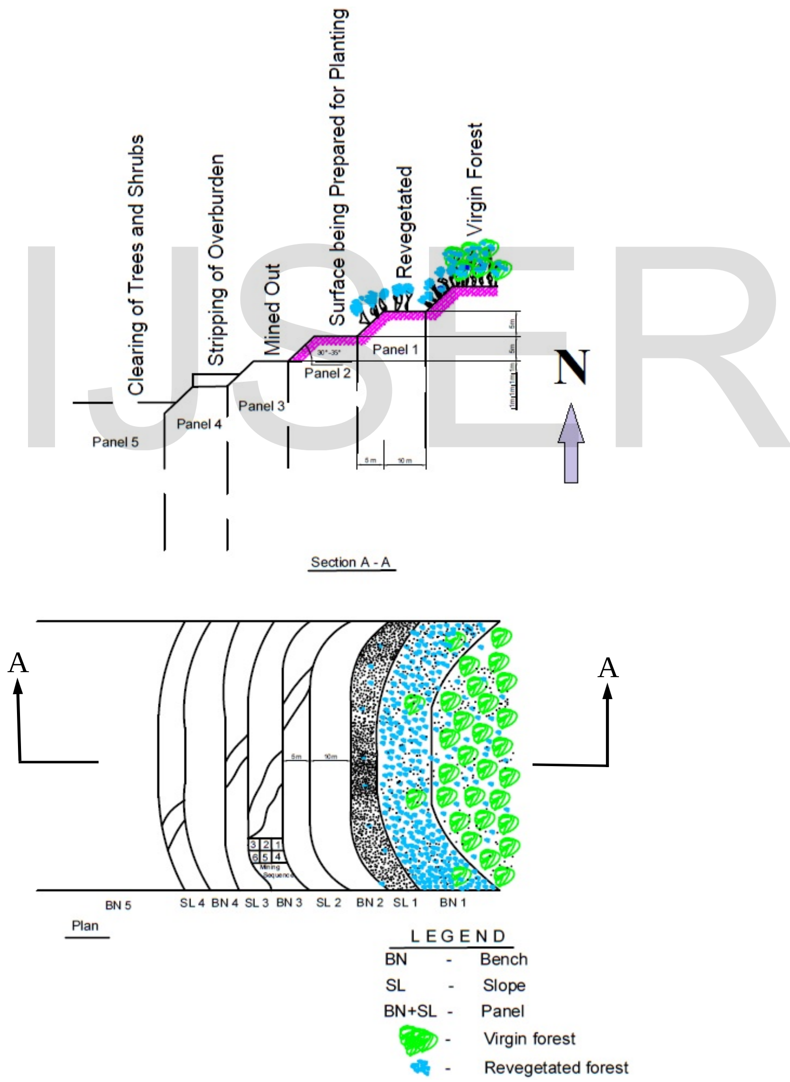

Fig.2 Proposed Terrace Mining Method for Weathered Gold Materials (Adapted from Mireku-Gyimah, 1995; Eshun and Mireku-Gyimah, 2002)

2.1.3 ShallowOpen Pit Mining Method

Shallow open pit mining method is proposed for the mining of auriferous lodes and quartz veins by the local operators in Nigeria whose mining activities are characterised by the use of manual techniques and equipment and, in other cases, limited technical competence. In this method, a typical deposit can be mined in benches of 3 m height down to a maximum allowable working depth of 15 m and overall slope angle of 32°. Thus, mining beyond 15 m depth is not allowed in shallow open pit method. Gibson *et al*. (2006) suggest the selection of suitable bench height, bench face angle and berm width for pit slope design to ensure slope facility. Fig. 3 shows the proposed shallow open pit mining method for ASGM operators.

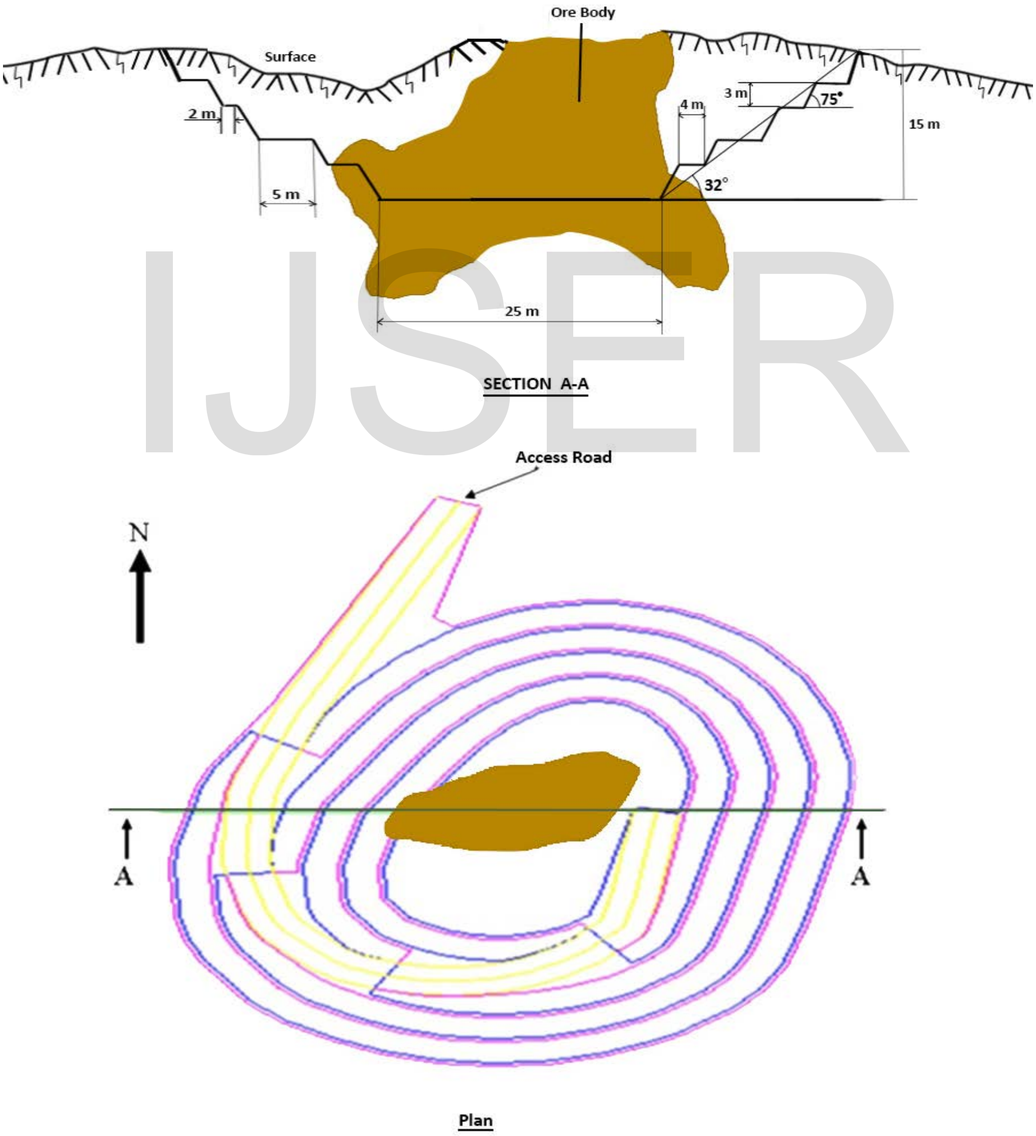

Fig.3 Proposed Shallow Open Pit Mining Method

*Selection of Pit Parameters:*To design the pit for the working of the proposed shallow open pit mining method by the ASGM operators, the following design parameters are considered based on geotechnical, safety and regulatory factors:

i. Bench height of 3 m;
ii. Bench width of 4 m;
iii. Berm width of 2 m;
iv. Ramp width of 5 m;
v. Total working depth of 15 m;
vi. Pit bottom width of 25 m;
vii. Bench slope angle of 75°;
viii. Overall slope angle of 32°; and
ix. Haul road gradient of 10 %.

2.1.4 Underground Mining Method

Underground mining method by adit or vertical shaft opening is proposed for the ASGM operators to exploit auriferous lodes and quartz veins in hilly terrains or flat plains which extend beyond the 15 m recommended working depth for the shallow open pit mining method. This proposal is necessary to provide viable economic, safety and environmental alternative for the local miners who have wider options of mining operations to choose from thereby ensuring compliance with best practices in the mining industry.In this method, mining is carried out in levels through a small adit or vertical shaft opening. Mining at an inter-level distance of 10 m up to maximum working depth of 50 m in each case is allowed. This is necessary to restrict miners' activities to safe and environmentally compliant working conditions underground. Fig. 4a and 4b show the proposed underground adit and vertical methods respectively.

*Selection of Underground Design Parameters:*The following parameters are considered for the proposed underground adit and vertical shaft ASGM based on geotechnical, safety and regulatory factors:

i. Maximum working depth of 50 m;
ii. Inter-level distance of 10 m;
iii. Adit slope angle of 5°;
iv. Inter-level diameter of 2 – 2.5m; and
v. Shaft/adit diameter of 2 – 2.5m.

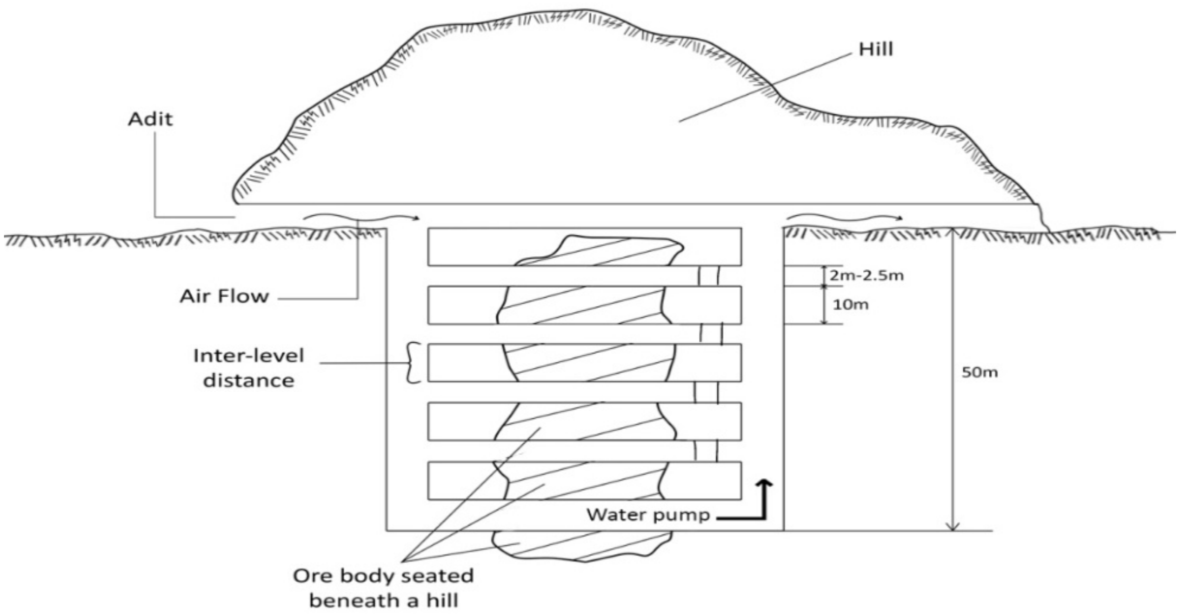

Fig.4a Proposed Underground Adit for Auriferous Lodes and Quartz Veins in Hilly Terrains beyond 15 m

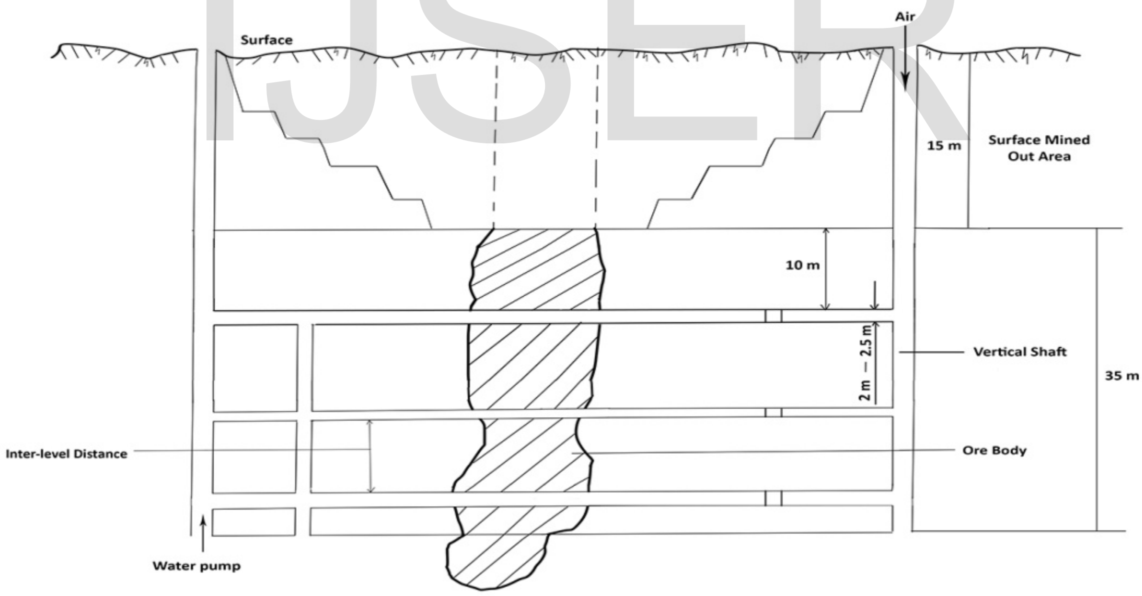

Fig. 4b Proposed Underground Vertical Shaft for Auriferous Lodes and Quartz in Flat Plains beneath 15 m

2.2 Processing Methods

Mercury free processing methods are recommended for the ASGM operators in Nigeria to eliminate the various environmental hazards associated with the use of mercury. The proposed processing methods include direct smelting method and "Igoli" processing technology. This proposal is based on careful study of the Nigerian ASGM terrain, types of deposits worked by the operators and their technical and financial status.

The proposed processing methods are not only mercury free but are also developed with a view to improving ore recovery in gold processing. Figs. 5 and 6 show the processing flow charts for the proposed direct smelting method for both free gold and hard rock deposits. The mixture of black sand containing gold, borax and soda ash, in some ratios, is heated by either charcoal or gas fired smelter until it is melted. The molten material is then poured to solidify. The borax lowers the melting of the solution, while soda helps the material to pour or flow easily after heating.

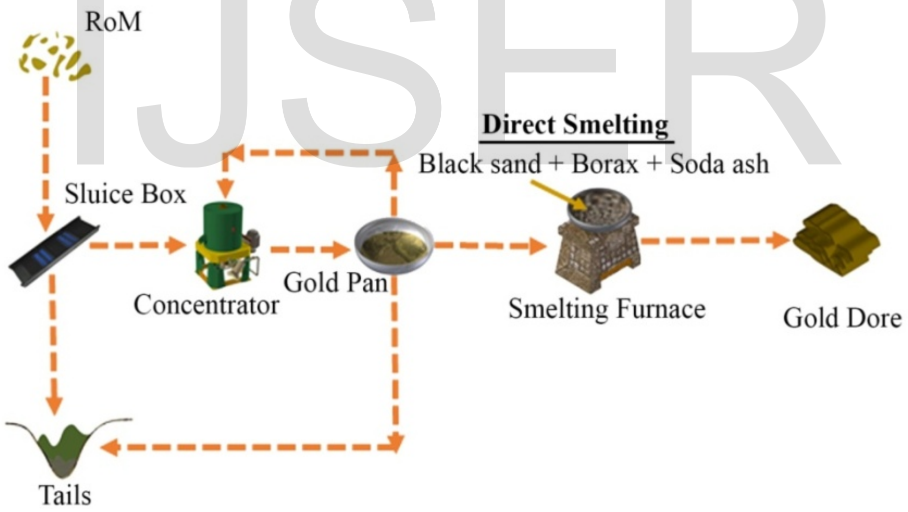

Fig. 5 Processing Flow Sheet of Direct Smelting for Alluvial Deposits

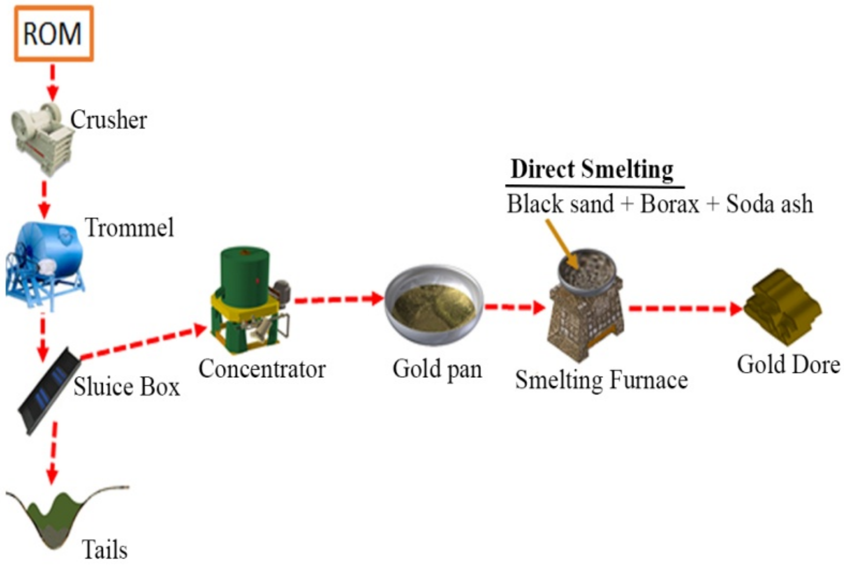

Fig.6 Processing Flow Sheet for Direct Smelting of Hard Rock Deposits

In igoli processing method, the gold ore is concentrated to obtain solid concentrate which is then leached through the addition of hydrochloric acid (HCl) and sodium hypochlorite (NaOCl) in equal quantities (15 %) to obtain dissolved gold. The solution is filtered to obtain concentrated gold solution which then goes through precipitation by the addition of sodium meta-bisulphite ($Na_2S_2O_5$) to obtain gold powder. Fig. 7 shows the processing flow chart of the proposed process.

To ensure effective management of water in gold processing, an outlet channel connected via the settling pond from the sluice box can be used to drain out clean water from the mud mixture. The clean water is then recycled back to the water reservoir connected to the washing area for reuse. The proposed water reticulation system for ASGM operators is shown in Fig. 8.

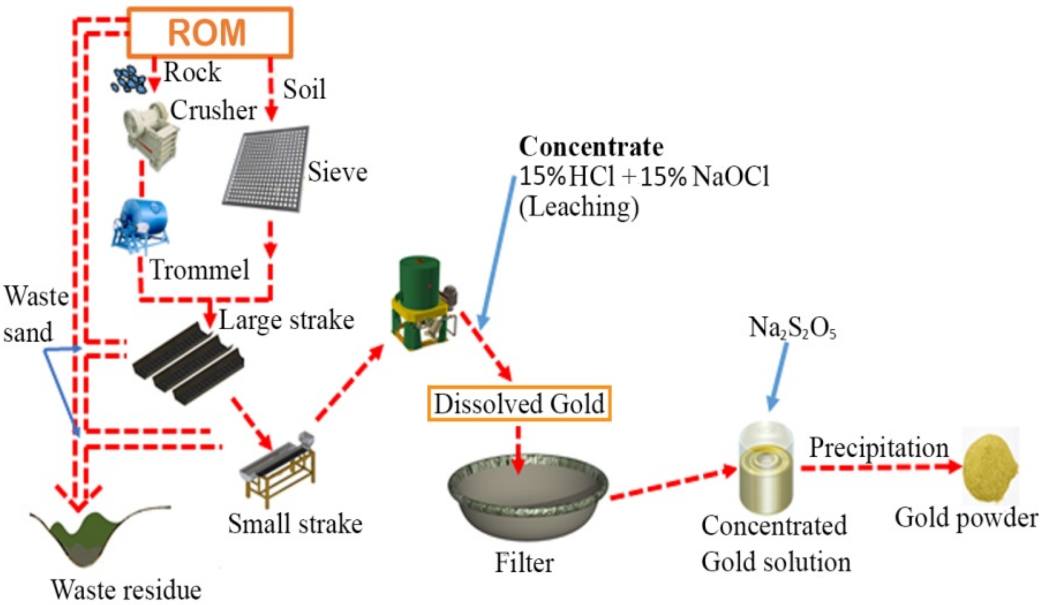

Fig. 7 Processing Flow Sheet of Igoli Technology

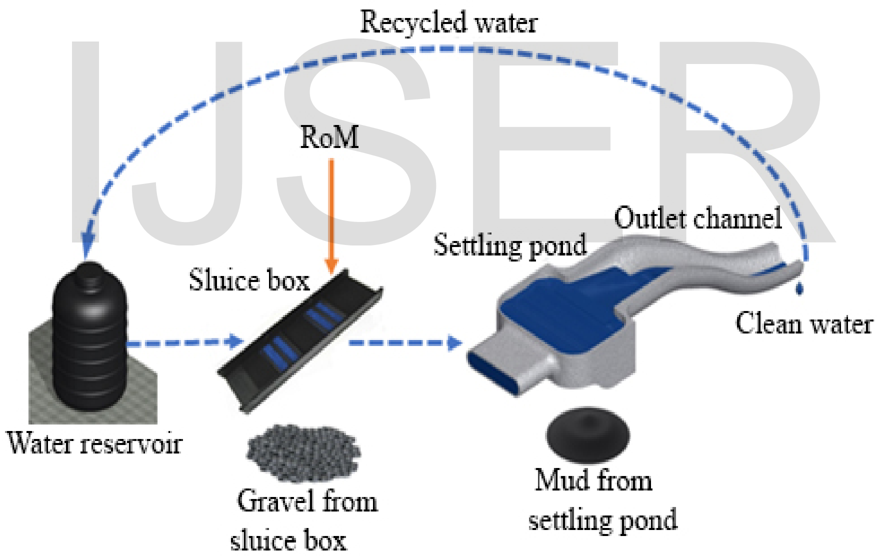

Fig. 8 Water Management/Reticulation System for ASGM in Nigeria

3. Proposed Equipment for Semi-mechanised ASGM

Suitable mining and processing equipment are proposed for semi-mechanised ASGM operations in Nigeria.The mining equipment selection is based on careful study of their availability,flexibility and suitability to weather conditions and working terrain in the Nigerian ASGM environment.

Tables 2, 3 and 4 respectivelyshow typical examples of selected surface, underground and gold processing equipment for semi-mechanised ASGM operations in Nigeria. The specification and estimated cost (in dollars) of such equipment are also shown to guide policy makers and investors on the choice of equipment procurement.

Table 2 Surface Mining Equipment Specification and Cost

Specification	Typical Example of Equipment	Cost (US $ x 10^3)
Blade capacity – 1.99 m^3 Blade width – 3.2 m Length – 4.3 m	CASE 750L Dozer	99 000.00
Capacity – 20 tonnes Width – 2.5 m Maximum speed – 50 km/hr	VOLVO BM5350B Truck	50 000.00
Working radius – 11.3 m Digging depth – 7.5 m Bucket capacity – 3.5 m^3 Width – 3.2 m	VOLVO EC650 Excavator	175 000.00
Overall length – 8.9 m Width – 2.5 m Blade width – 2.7 m	VOLVO G90 Grader	212 000.00
Bucket capacity – 4.5 m^3 Width – 2.5 m Length with bucket on ground – 8.8 m Reach at maximum lift and dump – 1.3 m	VOLVO L150G Wheel loader (Front-end-loader)	267 000.00
Tool diameter – 0.2 m Operating pressure – 2320 psi Impact rate – 300 bpm Hole diameter – 0.0254 m	SANHA S150S Hydraulic jack hammer	34 000.00
Capacity - 6 m^3/min Working pressure – 7 mpa Motor power – 37 hp/kW Applicable carrier weight – 25 tonnes	VOLVO VFY – 6/7 Air compressor	30 000.00
Pumping capacity – 538 litres (142 gallons) per minute Maximum head – 35 m Maximum pressure – 49.8 psi Suction discharge – 51 x 51 mm	HONDA GS120 Dewatering pump	656.00
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)	CUMMINS C150D5 150 kvA Diesel generator	38 000.00
10 % Miscellaneous		90 566.00
	Total Cost	**996 222.00**

Table 3 Underground Mining Equipment Specification and Cost

Specification	Typical Example of Equipment	Cost (US $ x 10^3)
Bore diameter: 34 mm Working pressure: 0.4 mpa Impact energy: 44 J Drill speed: ≥ 250 Mm/min	YT28 Underground jackhammer	315.00
U frame, air motor K-14H, pneumatic drive unit, fly wheel, chain coupling, *etc.*	VK Pneumatic raise climber	1 000.00
Material: 40 Cr steel Diameter: 25 mm Length: 1 m Capacity: 200 KN	SINOROCK R32S Hollow anchor bolt	35.00
Voltage: 110 V Power: 24.4 W Speed: 2450 m/s	WINCO 172*150*51 Fan	60.00/adit or shaft
Rotating speed: 2875 r/min Pump head: 40 m Motor power: 9.2 kw Matching pipe diameter: 89 mm	SHENWU 250QJ Water pump	780.00
Bucket capacity: 4.5 m^3 Width: 2.5 m Length with bucket on ground: 8.8 m Reach at maximum lift and dump: 1.3 m	VOLVO L150G Wheel loader	267 000.00
Capacity: 20 tonnes Width: 2.5 m Maximum speed: 50 km/hr	VOLVO BM5350B Truck	50 000.00
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)	CUMMINGS C150DS Diesel Generator	38 000.00
10 % Miscellaneous	Ancillary equipment: chains, hook blocks, hoist rope, shackles, *etc.*	35 719.00
	Total Cost	**392 912.00**

Table 4 Mineral Processing Equipment Specification and Cost

Specification	**Typical Example of Equipment**	**Cost (US \$ x 10^3)**
Capacity: 30 t/hr Maximum Feed size: 290 mm Power: 37 kW	PEV Jaw crusher	14 500.00
Capacity: 15 t/hr Power: 570 kw Weight: 92 tonnes	ZENITH Ball mill	5 000.00
Processing capacity: 1 t/hr Output particle size: 0.1 mm Feeding size: 50 mm	CPS50 Hammer mill	2 000.00
Screen mesh size: 4 mm Voltage: 110 v Frequency: 55 Hz	Vibrating screen machine	5 000.00
Capacity: 50 t/hr Feeding size: 80 mm Maximum input size: ≤ 230 mm	Small-scale gold trommel-scrubber wash machine	5 000.00
Length: 2.5 m Width: 1 m	JOBE Yellow jacket sluice box	93.00
Motor power: 1 kW Beneficiation area: 7.6 m^2	6S – 1.95 Gold separator shaking table	2 000.00
Capacity: 612 m^3/hr Head: 11 m Speed: 400 rpm Pump weight: 3750 kg	10/8 ST – AH Slurry pump	713.00
Heating power source: 45 kW Graphite ingot mould: 100 g	Gold smelting furnace	1 000.00
Capacity: 10 kg Readability: 0.1 g Power requirement: 90 – 250 v; 50/60 Hz; 10 watt Operating temperature: 10 – 45 ^{0}C Pan size: 190 x 250 mm	CT – 10001 Gold weighing scale	1 700.00
10 % Miscellaneous	Ancillary equipment/accessories	3 701.00
	Total Cost	**40 707.00**

4. Manpower Requirements for Semi-mechanised ASGM

The manpower required for the proposed semi-mechanised ASGM comprises the following:

- Site manager x 1;
- Mining engineer x 1;
- Mineral engineer x 1;
- Foreman x 1;
- Mine workers x 15
- Equipment operators x 5; and
- Driver x 1.

The minimum required qualification for the personnel in the proposed semi-mechanised ASGM is recommended based on the level of education attained, relevance of the field of specialisation to ASGM and requisite field or industrial experience of the personnel. The following categories of workers are required to form the workforce of the proposed ASGM:

- Skilled/technical workers;
- Semi-skilled workers; and
- Unskilled workers.

The following aspects of equipment maintenance are recommended for effective management of the proposed ASGM equipment:

- Equipment servicing and repairs;
- Fleet management;
- Protection of ASGM equipment and accessories; and
- General security of ASGM personnel;

5. Conclusions and Recommendations

Theproposed methods and recommended equipment are meant to ensure sustainable and environmentally friendly ASGM operationsin Nigeria. They would enable the operators standardise their operations to an acceptable level in line with best global mining practices, while contributing immensely to the national economy and mitigating casualties associated with inefficient ASGM to the barest minimum.

It is,therefore, strongly recommended that the proposed mining and processing methods should be adopted by the ASGM operators to ensure sustainable and environmentally friendly ASGM operations. Successfuladoption of the methods is, however, subject to effective reclamation, waste disposal and flood control measures inASGM operations. Policy makers in Nigeria should facilitate successful adoption of the proposed methods by giving adequate supports to the local miners and properly integrating them into formal mining sector.

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