Determination of Depleted Rock Volume in Open Cast Mines Using Photogrammetric Techniques for the Purpose of Royalty Calculation

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Abstract
In Sri Lanka, Geological Survey and Mines Bureau (GSMB) imposed royalty levy for aggregate production volume using an equation (indirect method) which utilises the quantity of explosives for the calculation. Since the equation resulted in higher deviations and the previous studies emphasise the advantages of photogrammetric 3-dimensional (3D) modelling (direct method) when determining production volume of bench blast, the present study focus on investigating its applicability to irregular faced dynamic quarry with uneven overburden. Pre and post 3D Digital Surface Models (DSMs) of the quarry were generated using the structure from motion (SFM) algorithm with Real-Time Kinematic (RTK) positioning system and Pix4D mapper software. Golden Software Surfer 16 was used to determine depleted rock volume as the difference between pre and post 3D DSMs. Results indicate a 5.50% deviation of the proposed method from true depleted rock volume determined by truck measurements due to uncleaned quarry face during the pre-Drone survey and unaccounted soil overburden removal. Presence of overburden while generating DSMs can be overcome by pile volume estimation of overburden and decreasing it from depleted rock volume when calculating production volume. GSMB equation calculated production deviate -32% from true production due to the unaccounted explosive amounts which contributed to the production and confirm the suitability of the proposed direct method (5.5% deviation) for determining the depleted rock volume in open-cast mines.

Keywords: Digital surface model, Drones, Pix4D, Real-Time Kinematic positioning

1. Introduction

The mineral wealth of Sri Lanka is regulated by the Geological Survey and Mines Bureau (GSMB). GSMB uses a hybrid system composed of unit-based and value-based systems for royalty calculation of aggregate products [1]. Equation 1 was presented by the Defence Ministry of Sri Lanka and utilised by the GSMB when calculating aggregate yield volume in cubes until 2019 [1].

$$\text{Yield} = 2 \times (a + b) + c \qquad (1)$$

Where,

Yield volume in cubes

a	Amount of water gel used (kg)
b	Amount of ANFO used (kg)
c	Amount of black powder used (kg)

Equation 1 depends on the amount of explosives used for the blast, and its origin have not been proved scientifically [1,2]. Further, Equation 1 does not provide a clear understanding about the impact from the grade of the quarry and bulking of materials. Later in 2019, a new equation (Equation 2) was introduced based on powder factor, bulking factor and explosive amount.

$$\text{Yield} = ((a \times \text{RWS} + b)/\text{PF}) \times \text{BF} \qquad (2)$$

Where,

Yield volume in m^3

a	Amount of water gel used (kg)
b	Amount of ANFO used (kg)
RWS	Relative Weight Strength of water gel
PF	Powder factor (kg/m^3)
BF	Bulking factor (1.6)

The relative weight strength of watergel was taken as 1.2 in Equation 2. Moreover, factors like the Industrial Mining Licence (IML) category of the quarry, drilling depth, borehole diameter, production and explosive amount were considered when allocating powder factors as stated in GSMB Circular no. 189/01/2021. However, bulking factor was taken as a universal constant which equals to 1.6, regardless of fragmentation, particle size and blasting parameters.

Jayawardana et al. [1] and Perera et al. [2] recommended deploying photogrammetric 3D modelling to calculate the depleted (production) volume of quarries instead of explosive based equations since the results obtained by Drone surveys were deviating -5% from true depleted volume. However, they [1], [2] conducted Drone surveys for bench blasting, and the applicability of the method for the entire quarry was not examined. Besides, the applicability of photogrammetric 3D modelling for small scale quarries with extremely irregular quarry face is unknown. Therefore, the applicability, pros and cons and solutions for encountered complications when employing photogrammetric 3D modelling to a dynamic quarry having irregular quarry face with a weathered rock and soil overburden have been investigated in this study.

2. Methodology

True depleted rock volume was determined using truck measurements compared with depleted rock volume determined by the Drone survey to validate the applicability of photogrammetric 3D modelling in determining aggregate yield volume for the purpose of royalty calculation.

2.1 Site Selection

The study was carried out by selecting an IML C category quarry which is located in Bathalawatta, Dambugolla, Ambepussa in Sri Lanka. Irregular faces, unavailability of benches, topsoil overburden with weathered rock layer are the main features identified. Explosive usage and production were monitored for a time period of four months.

2.2 Determination of depleted rock volume using truck measurements

In-situ production volume and in-situ waste rock volume were calculated using truck weights and truck volumes, respectively. Depleted rock volume was calculated by adding in-situ production volume and in-situ waste rock volume. Depleted rock volume determined by this method was considered as the true value.

2.2.1 In-situ production volume

Truck weights of blasted rocks (tons) were measured to determine the in-situ production volume. The specific gravity of the rock samples obtained from the quarry site were tested in the laboratory to estimate the average density of the rock (kg/m^3), and in-situ production volume (m^3) was calculated using Equation 3.

$$\text{Volume} = \frac{\text{Tonnage hauled x 1000}}{\text{Density of rock}} \qquad (3)$$

2.2.2 In-situ waste rock volume

Truck volumes of bulk waste rocks (cubes) were recorded and converted to in-situ waste rock volume (m^3), assuming the bulking factor as 1.6.

2.3 Determination of depleted rock volume using aerial photogrammetry

Aerial images can be used in generating the 3D model of an object and obtain accurate measurements such as distance, area and volume. This method can be used to obtain a 3D DSM of the quarry.

2.3.1 Drone surveying for 3D modelling

In this study, pre and post Drone surveys were conducted for the purpose of generating 3D DSMs.

2.3.2 Data acquisition

DJI Phantom 4 Pro Drone was used to obtain the aerial images. Specifications of the Drone are indicated in Table 1.

Prior to conducting the Drone flight, Ground Control Points (GCPs) were marked on permanent structures or places that would not be removed until the next survey was conducted. Coordinates of each GCPs were recorded using a highly accurate RTK positioning system during the pre-Drone survey.

A drone survey was conducted after selecting a suitable height, ground sampling distance and grid pattern to cover the project area.

2.3.3 Data processing

Data processing was done using two software viz.

1. Pix4D mapper
2. Golden Software Surfer 16

Aerial images of pre and post surveys were processed using the Pix4D, and georeferenced DSMs were generated (Spatial resolution 2.84cm per pixel). Pre and post-survey DSMs were developed in Surfer software in colour relief format, and the area of which the volume should be calculated was demarcated. Depleted rock volume was determined as the difference in volumes of the same area in pre and post-survey DSMs.

Table 1: Specifications of the Drone.

Model	DJI Phantom 4 pro
Weight	1388 g
Max speed	P-mode: 31 mph (50 kph)
Max flight time	Approx. 30 minutes
Satellite positioning systems	GPS/GLONASS
Max wind speed resistance	10 m/s
Operating temperature range	32° to 104° F (0° to 40° C)
Camera sensor	1′′ CMOS Effective pixels: 20M
Lens	FOV 84° 8.8 mm/24 mm (35 mm format equivalent) f/2.8 - f/11 auto focus at 1 m - ∞
Gimbal stabilization	3-axis (pitch, roll, yaw)
Battery capacity	5870 mAh
Battery type	LiPo 4S
Voltage	15.2 V
Remote controller operating frequency	2.400 - 2.483 GHz and 5.725 - 5.825 GHz
Max transmission distance	7 km

2.4 Determination of yield volume using equations utilised by the GSMB

Explosive quantities consumed during the study period were recorded and used in Equations 1 and 2 to determine the yield volumes.

3. Results

3.1 Calculation of depleted rock volume using truck measurements

3.1.1 Density of the rock

The specific gravity of rock samples (Table 2) was obtained by performing laboratory tests based on Archimedes' principle, and the average density of the rock was derived, assuming the density of distilled water as 1000 kg/m^3.

Table 2: Specific gravity and average density of rock.

Sample	Specific gravity	Average density (kg/m^3)
1	2.67857	2671.11
2	2.66154	
3	2.68148	
4	2.65957	
5	2.67442	

3.1.2 Calculation of in-situ production volume

Production values (tons) were obtained by measuring truck weights of the blasted rocks with the use of a weighbridge (Table 3).

Table 3: Tonnage of blasted rock.

Period	Production (tons)
11th March – 31st March	3155
April	2850
May	4855
June	1800
1st July - 17th July	2150
Total Production (tons)	**14810**

The average density of the rock (Table 2) and total production tonnage (Table 3) were substituted in Equation 3 to compute the in-situ production volume as 5544.51 m^3.

3.1.2 Calculation of in-situ waste rock volume

Waste rocks were not weighted, but instead, broken waste rock volume was measured using truck volumes (cubes) and converted to in-situ waste rock volume. The bulking factor was assumed as 1.6 (as declared by the GSMB) (Table 4).

Table 4: Waste rock volumes.

Period	Waste rock volume	
	Bulk (Cubes)	In-situ (m^3)
11th March – 31st March	51	90.24
April	27	47.77
May	48	84.93
June	21	37.16
1st July - 17th July	18	31.85
Total	**165**	**291.95**

In-situ production volume and in-situ waste rock volume were added to determine the depleted rock volume by truck measurements (Table 5).

Table 5: Volumes calculated by truck measurements.

In-situ production volume (m^3)	In-situ waste rock volume (m^3)	Depleted rock volume (m^3)
5544.51	291.95	5836.46

3.2 Calculation of depleted rock volume using Drone surveys

Figure 1 illustrates the generated DSM of the pre-Drone survey. The demarcated boundary of pre and post-survey models in colour relief format generated using Golden Software Surfer 16 (given in Figure 2 and Figure 3, respectively.)

Volumes calculated from the surfer software are presented in Table 6. Volume of the post survey was subtracted from the pre survey to determine the depleted rock volume (in-situ) by Drone surveys.

Figure 1: DSM of the pre-Drone survey.

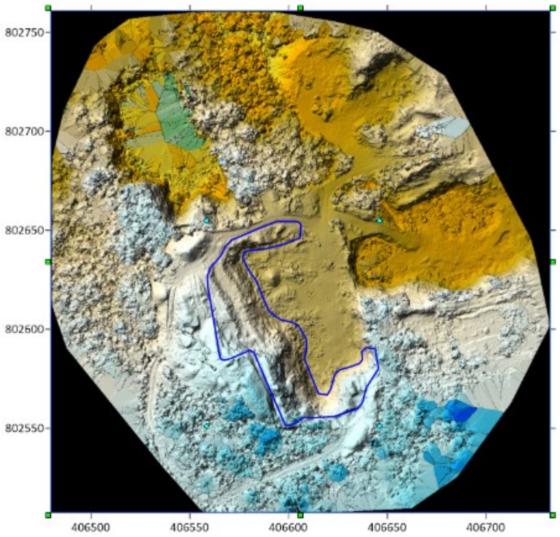

Figure 2: Pre-Drone survey DSM colour relief format with demarcated boundary.

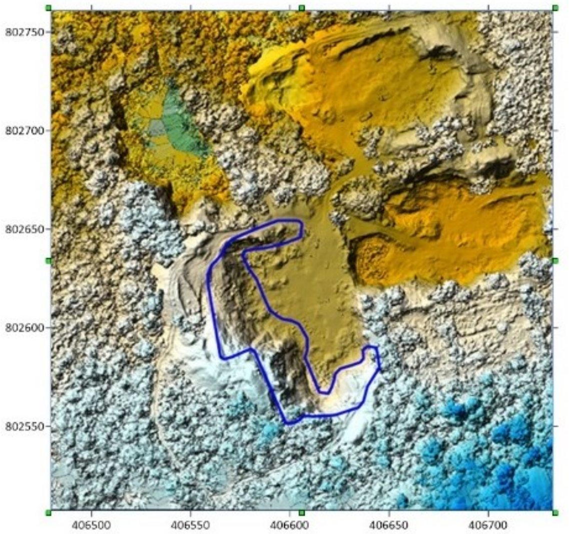

Figure 3: Post-Drone survey DSM colour relief format with demarcated boundary.

Table 6: Volumes calculated by surfer software.

Pre survey volume (m^3)	**Post survey volume (m^3)**	**Depleted rock volume (m^3)**
56403.70	50246.16	6157.54

3.3 Calculation of production volume using explosive based equation

Utilised explosive quantities (Table 7) recorded during the study period were used in Eq1 to calculate bulk production volume by explosive based equation. The bulking factor was assumed as 1.6 when converting bulk volume to in-situ volume (Table 8).

Table 7: Explosive utilisation during the study period.

Explosive	**Amount (kg)**
Water gel	92
ANFO	865

Table 8: Production volume calculated by explosive based equation.

Bulk volume (cubes)	**In-situ volume (m^3)**
1914	3386.58

3.4 Calculation of production volume using powder factor based equation

Similarly, utilised explosive quantities (Table 7) during the study period were used in Equation 2 to calculate bulk production volume by powder factor based equation. According to the selected quarry type, PF and BF in Eq2 were taken as 0.259 kg/m^3 (based on GSMB Circular no. 189/01/2021) and 1.6, respectively. Estimated bulk production volume was divided by BF to determine in-situ production volume calculated by powder factor-based equation.

Table 9: Production volume calculated by powder factor based equation.

Bulk volume [m^3]	In-situ volume [m^3]
6025.63	3766.02

4. Discussion

Depleted rock volumes determined by truck measurements (M1) and Drone surveys (M2) are tabulated in Table 10. M2 shows 5.50% deviation from M1 (true value) (Table 10). Unaccounted removal of weathered rock overburden during study period resulted in volume reduction of M1 as well as the presence of blasted rock on quarry face during pre-Drone survey resulted in volume exaggeration of M2. Uncleaned blasted rock (bulk volume) on quarry face was identified as the in-situ volume when determining M2. Deviation of M2 can be minimised by clearing the quarry face before Drone surveys and, in addition, by improving the resolution.

Table 10: Comparison of depleted rock volume calculated by each method

Method	**Depleted rock volume (m³)**	**Absolute deviation (m³)**	**Relative deviation (%)**
M1	5836.46	-	-
M2	6157.54	321.08	5.50%

M1: Depleted rock volume determined by truck measurements (true value)

M2: Depleted rock volume determined by Drone surveys

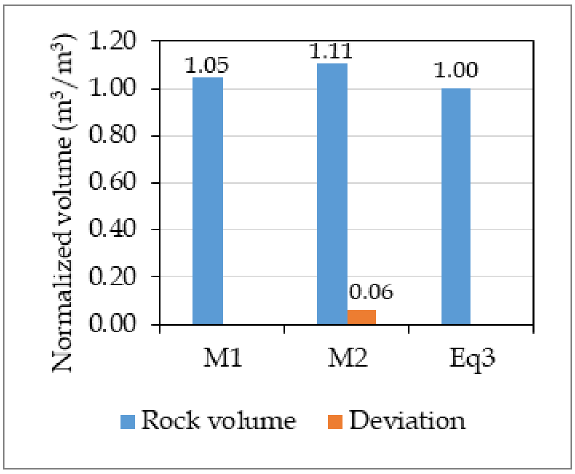

Figure 4: Depleted rock volume comparison (refer Table 10 for M1 and M2; Table 11 for Equation 3)

Figure 4 illustrates the depleted rock volumes obtained by truck measurements (M1) and Drone surveys (M2) normalised by production volume (5544.51 m³) calculated using tonnage (Equation 3). Figure 4 indicates that 1.05 m³ of rock should be excavated to produce 1 m³ of aggregate due to the weathered rock layer existing in the studied quarry. Moreover, M2 shows 0.06 m³/m³ deviation (discussed 5.50% relative deviation, Table 10) with reference to M1 as a result of preventable reasons (Figure 4).

Table 11: Comparison of production volume calculated by each equation.

Equation	**Depleted rock volume (m³)**	**Absolute deviation (m³)**	**Relative deviation (%)**
Eq1	3386.58	-2157.93	-39
Eq2	3766.02	-1778.49	-32
Eq3	5544.51	-	-

Eq1: Production volume calculated by explosive based equation

Eq2: Production volume calculated by powder factor based equation

Eq3: Production volume calculated by tonnage (true value)

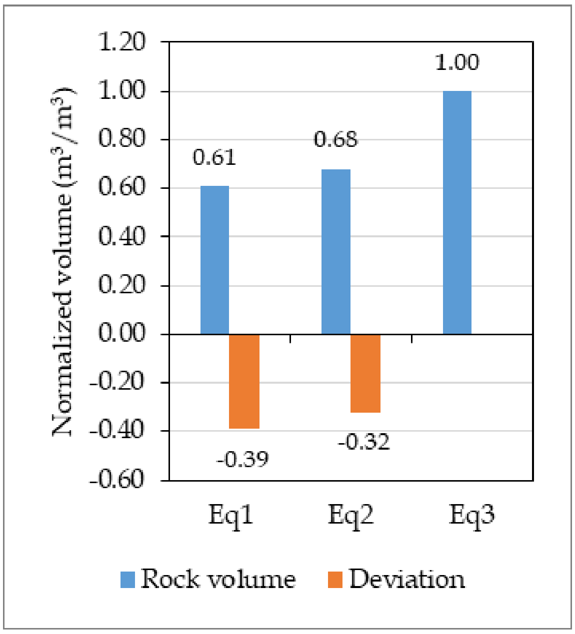

Figure 5: Production volume comparison (refer Table 11 for Eq1, Eq2 and Eq3)

Table 11 includes the production volumes calculated by explosive based equation (Equation 1), powder factor based equation (Equation 2) and directly estimated tonnage (Equation 3). Equations 1 and 2 show -39% and -32% relative deviations from Equation 3 (true value) respectively (Table 11). The relative deviation of Equation 1 from Equation 3 was -18% and -8% - +34% when computing the results obtained by Jayawardana et al. [1] and Perera et al. [2], respectively. Relative deviations obtained by the present study indicate intense negative value compared to previous studies [1, 2]. The reason for such intense deviation was due to the presence of uncleaned blasted rock on the quarry face, which resulted from blasts conducted prior to the pre-Drone survey. The weight of said uncleaned blasted rock was counted to tonnage (Equation 3) since it was removed from the quarry as production during the study period. However, the used explosive amount for the said uncleaned blasted rock was not counted to explosive utilisation during the study period (Equations 1 and 2) since those blasts were conducted prior to the pre-Drone survey.

Figure 5 shows the production volumes obtained by explosive based equation (Equation 1) and powder factor based equation (Equation 2) normalised by production volume (5544.51 m^3) calculated by tonnage (Equation 3). Equation 2 exhibit a 0.07 m^3/m^3 increase than Equation 1. However, production volume calculated by Equations 1 and 2 deviates from the true value (Equation 3).

Equations 1 and 2 depends on the utilised explosive amount. Although these equations calibrate to calculate quarry production, they may not derive quarry production accurately during a specified period, possibly due to unaccounted explosive amounts which contributed to the production, similar to the situation encountered during the present study. Conversely, depleted rock volume determined by Drone surveys indicates an acceptable correlation with the depleted rock volume determined by truck measurements (true value) (Figure 4), validating the applicability of the proposed Drone-based method to calculate the depleted rock volume in quarries. In addition, a Drone survey consists of less data acquiring time and straightforward data processing. Further, volume calculation using DSM is an accurate and efficient method that can deploy to determine depleted rock volume in quarries.

Inability to calculate the depleted overburden volume directly by generating pre and post-survey DSMs counted as the disadvantage of this method. However, collected and piled overburden volume can be estimated using a Drone survey [1]. Thus, the disadvantage of the method can be eliminated by utilising the pile volume determination method, which needs training and expertise on drone surveys.

5. Conclusion

Results obtained by the study confirm the suitability of the suggested Drone-based methodology for calculating the depleted rock volume in open-cast mines for the purpose of Royalty calculation.

Furthermore, the present study confirmed the inapplicability of equation-based methodology, which cause significant production volume deviations.

Problems encountered during the implementation of the proposed methodology can be eradicated by following the solutions recommended in the study. Finally, the current loss of revenue to the national economy due to erroneous estimation of aggregate production can be reduced significantly by implementing the suggested method.

6. Recommendations

If the proposed method is selected to determine the aggregate production volume by the GSMB, the following precautions should be adopted as standards to acquire true in-situ rock DSM.

- Quarry face should be free from loosen rock prior to Drone survey.
- Quarry floor should be cleared at least 3 m distance from the toe.

Moreover, frequent Drone surveys are recommended for accurate results.

The applicability of the proposed methodology to other types of open cast mines (such as limestone, quartz and feldspar) should be examined further.

Acknowledgement

The authors wish to extend their sincere gratitude to all academic and non-academic staff of the Department of Earth Resources Engineering in the University of Moratuwa for their assistance throughout this study. Special thanks are also due to Mr. Nalin De Silva, Director (Mineral Survey) and Mr. SB Harankahawa, Geologist of GSMB, who gave immense support for this research providing us with necessary assistance. We would also like to express our sincere gratitude to Eng. HND Padumasiri, the Mining engineer of the quarry and all the staff in the quarry for providing their workplace to do our research.

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