Control of Ore Loss and Dilution at AngloGold Ashanti, Iduapriem Mine using Blast Movement Monitoring System*

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Abstract

Blast Movement Monitoring (BMM) system is a new method of determining material movement during blasting in order to minimise ore loss, dilution and sometimes misclassification. The BMM system was introduced at AngloGold Ashanti Iduapriem (AAIL) Mine in the first quarter of 2013 as a result of reconciliation challenges at the start of operation at the Ajopa Pit in the first quarter of 2012. Since the introduction, there has been improvement in reconciliation, but the cost implication became worth assessing because of dwindling gold price. The main objective of this paper, therefore, is to assess the benefits or otherwise of BMM system on blast induced movement at Iduapriem Mine. The study comprises data collection on BMM system at AAIL and its analysis, as well as cost and benefit analysis. From the BMM data analysis, it was observed that, the bottom flitch of the blasted material moved more than the top flitch in the horizontal direction while the reverse was the case for the vertical movement. The cost-benefit analysis from four shots analysed revealed that there was a benefit of $753 835 which translates into 650% return on investment. Thus, the use of the BMM system has positive financial impact on Iduapriem Mine. Continuous use of the system as a grade control practice has, therefore, been recommended for the Mine, especially with shots containing ore. Furthermore, a dedicated team for this task has been recommended to enhance efficiency. Finally, high precision GPS has been suggested to be added to the detector instrument to make surveying of pre-blast and post-blast BMM points easier and faster.

Keywords: Blast Movement Monitoring System, Ore Loss, Dilution, Misclassification, Reconciliation

1 Introduction

Blasting causes movement of the rock and can be detrimental to the accurate delineation of the ore and waste regions within the resulting muckpile. The consequences can be post-blast ore loss (moving ore to waste dump), dilution (mining waste with ore), and misclassification (part of a block moving into another block).

Reducing the amount of ore loss and dilution of Run-of-Mine (ROM) ore prior to processing is the goal of most metal mining companies. The addition of waste to ROM ore for processing as a result of blast movement lowers the overall expected mill head grade. This could lead not only to poor reconciliation but also affect the economic viability of the mining business. Costly extensive grade control drilling, assaying and time consuming computerised orebody modelling become meaningless if the pre-blast ore perimeters defined are not translated after blasting before excavation, to account for blast movement. Therefore, ore loss and dilution can be minimised and significant increases in profit can be realised if the movement of the blast can be accurately measured.

Over the years, AngloGold Ashanti Iduapriem Limited (AAIL) has had challenges with grade and tonnage reconciliation of material mined from its pits, especially the Ajopa pit. There was about 10% drop in the accountable metal from the start of mining at Ajopa from October, 2012 to the 1st quarter of 2013.

One way of addressing this challenge was the introduction of the Blast Movement Monitoring (BMM) system to monitor the movement of the ore after blasting and also to adjust the ore outlines before mining. However, the cost implication became a matter of concern as a result of dwindling gold price. This paper therefore presents a study of the BMM system at AngloGold Ashanti Iduapriem Mine and an assessment of the benefits or otherwise of the system to the Mine.

1.1 About the Study Area

1.1.1 Location and Accessibility

AngloGold Ashanti Iduapriem Limited (AAIL) is a subsidiary of AngloGold Ashanti Company. It comprises two properties i.e. Iduapriem and Teberebie. Both properties are located in the Western Region of Ghana, some 70 km north of Takoradi, the Regional capital and 10 km south-west of Tarkwa. It is 233 km from Kumasi, the second largest city in Ghana and about 322 km from Accra, the national capital. AAIL is located along the southern end of the Tarkwa basin (Anon., 2013). The mine is accessible by road from Kumasi and Takoradi. Fig. 1 shows the location of AAIL on the map of Ghana.

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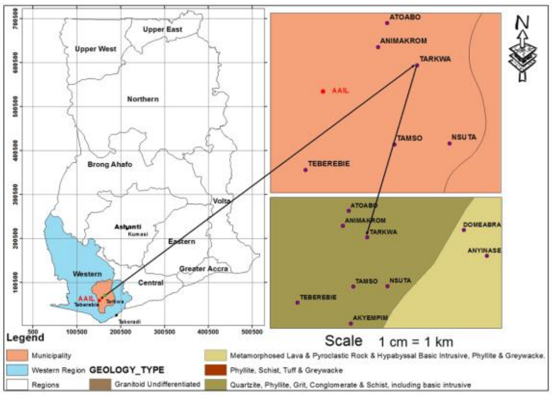

Fig. 1 Map of Ghana showing the Location of AAIL (Source: Authors' Construct)

1.1.2 Physiography

The relief of the area is characterised by series of undulating landscape with prominent ridges that are about 60 to 80 metres above mean sea level (Anon., 2013). The ridges which form the four main specific mining areas are: Blocks 1 to 5; Block 6 (Ajopa); Blocks 7 (Teberebie); and 8 (Awunaben). Fig. 2 is a map of a section of the Tarkwa district showing the Iduapriem mining lease.

1.1.3 Deposit Geology

All gold mineralisation occurs within the four specific zones or reefs and are not related to metamorphic and hydrothermal alteration events. The gold is fine-grained, particulate and free milling (i.e. not locked up with quartz or iron oxides). Mineralogical studies indicate that the grain size of native gold particles ranges between 2 and 500 µm and averages 130 µm. Sulphide mineralisation is present only at trace levels and is not associated with the gold (Baffoe, 2004).

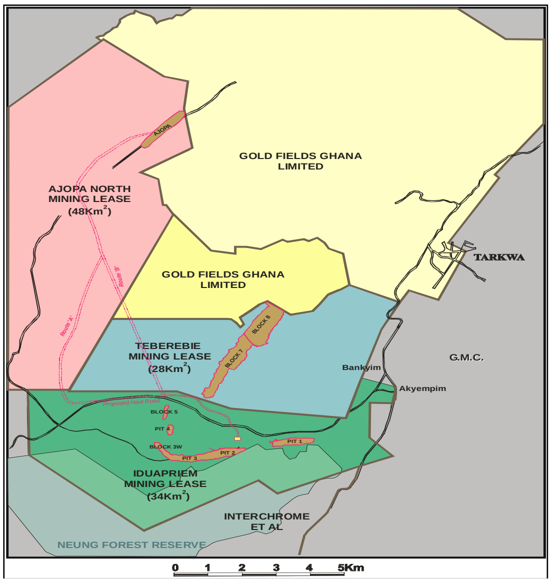

Fig. 2 Map showing the Iduapriem Mining Lease (Source: Anon., 2013)

1.1.4 Mining Operations

Mining operations are conducted using conventional open pit mining method. This employs four standard unit operations namely drilling, blasting, loading and hauling. At the time of the study, mining operations were contracted to AMS Limited, a subsidiary of the Ausdril Group of companies in Australia.

The drilling operations are done by AMS employing three (3) Pantera, four (4) Rock Commander, and two (2) Drilltech drill rigs. Drilling parameters include 6 m bench height with 1 m sub-drill and hole diameter of 127 mm for production holes and 102 mm for pre-split. The current blast pattern is staggered with 4.2 m burden by 4.6 m spacing for both ore and waste. Blasting employs down-the-hole delay firing using electric initiation system. Explosives and accessories are supplied by Maxam Ghana Limited. Powder factor is normally around 0.52 kg/m^3.

At Ajopa pit, the load and haul operation is carried using one (1) Liebherr 9250 excavator and one (1) Liebherr 984 excavator as back-up with eight (8) 92-tonne capacity haul trucks. Two (2) of the 8 trucks are mostly on stand-by. The material is mined and dumped onto a stockpile at Ajopa by AMS and later transported by Maxmass Company, a local contractor, to the crushing plant. Maxmass uses FM400 Volvo Tipper trucks for the re-handling.

1.2 Blast Movement Monitoring

The aim of rock excavation in an open pit mine is to produce an optimum mill feed with minimum dilution to maximise recovery at a minimum operating cost. Little and Van Rooyen (1988) were among the first to identify blast-induced dilution as a significant grade control problem.

A number of sites and research institutions have used a range of measurement techniques with varying success. These can be categorised by the type of marker employed: passive visual ones such as sand bags, chains and pipe; and remote detection systems such as blast movement monitors and magnetic markers that can be detected prior to excavation of the blasted ore (La Rosa and Thornton, 2011).

Yang and Kavetsky (1989) developed a two-dimensional model with a simple kinematic approach for predicting the muckpile shape in bench blasting. This model could be calibrated in a straight-forward manner using the blast parameters and the results could be used to analyse alternative blasting designs. They further developed an extension to the model in 1990 which resulted in a three-dimensional model of muckpile formation and grade boundary movement in bench blasting. These models include the blast design geometry, initiation, and explosive energy. Limited data from a case study were used to calibrate the models.

Lucas and Nies (1990) implemented two programmes at Homestake McLaughlin Mine; one to minimise the ore displacement, ground vibration and maintain good fragmentation with sequential timing, and the second to evaluate the orientation of delay pattern to the apparent rock structure. By reducing the powder factor in proportion with small blast holes, the explosives energy distribution was accomplished.

Zhang (1994) and Zhang *et al.*, (1994) investigated the blast-induced rock movement and its impact on grade control at Rain mine and Coeur Rochester mine. Six blasts at Rain mine and twelve blasts at Coeur mine were monitored. The study found out that:

- (i) The powder factor and the magnitude of the movement of the blast pattern were directly related; and
- (ii) The primary horizontal blast movement direction was approximately parallel to the initiation direction of each blast.

Zhang *et al.*, (1994) also suggested that in order to minimise the grade dilution, it is necessary to direct the blast in the deposit's strike direction with a single initiation point.

Taylor (1995) proposed the survey of pre and post-blast positions of solid marker objects. Solid markers are bags filled with rock-dust and placed in blast holes within the bench. Extra holes were drilled along with the normal drill holes with their known pre-blast locations. Usually these extra holes were drilled near the ore/waste boundary. The marker bags were placed in the extra holes which were devoid of explosives. After the blast, the rock was excavated and the post-blast positions of the bags were surveyed.

Taylor’s method has some disadvantages which limit its effectiveness. It is labour intensive and time consuming, particularly the post-blast survey, extra drill holes are needed which increases the drilling cost. There can be low recovery of the markers due to:

- (i) Difficulty in seeing the bags in the muckpile during the night shift;
- (ii) Incorrect identification of marker bags by shovel operators;
- (iii) Delayed movement information for correcting the digging polygons; and
- (iv) Efficiency of the technique is dependent on the ability of the shovel operators to discover the targets in the muckpile after the blast.

In 2004, Adam and Thornton described that the movement of ore within a blast can have significant economic impact on open pit mines. Blasting of the valuable mining blocks causes movement of the rock and is detrimental to the accurate delineation of the ore and waste regions within the muckpile. They used the electronic blast movement monitor developed by Julius Kruttschnitt Mineral Research Center (JKMRC), which provides 3-dimensional movement vectors following a production blast. With this information, the ore block boundaries in the blasted bench were adjusted to compensate for the measured movement and ore recovery. They concluded that "the development of JKMRC Blast Movement Monitors (BMM®s) showed the system to be reliable, easy to use and predict the blast movement (Adam and Thornton, 2004).

In 2005, the Blast Movement Monitoring (BMM) was conducted by Placer Dome Inc., at Porcupine mine (Yennamani, 2010). The major considerations while designing BMM holes were the size and shape of the pattern, the amount and location of ore and the direction of the blast. The BMM®s were used on a regular basis almost in every blast containing ore. It was observed that the direction of the movement was fairly predictive but the distance of the movement had some significant variations.

Research at the University of Queensland resulted in the development of an active blast movement marker (Thornton, *et al.*, 2005; Thornton, 2009a and Thornton, 2009b) and subsequent commercialisation by Blast Movement Technologies (BMT). According to Loeb and Thornton (2014), “an innovative technology has been developed and commercialised so that open pit mine operation personnel can measure three dimensional movement in every production blast”.

As concluded by La Rosa and Thornton (2011), “there is an increasing awareness of the magnitude and variation of blast movement and its economic implications. Since practical methods are now available to routinely measure blast movement, there is a compelling case for all mines to include blast movement measurement into their grade control procedures”.

In Ghana Engmann *et al*. (2013) validated the use of BMM system at Newmont Ghana Gold Ltd, Ahafo Mine. This paper studies the application of the system at AngloGold Ashanti, Iduapriem Mine and conducts cost-benefit analysis of the implementation of the system.

1.3 BMM System Instrumentation

The measurement and analysis of rock movement using BMM system require the following equipment:

(i) BMM® Ball (Sensor);
(ii) BMM® Activator;
(iii) GP5200 BMM® Detector;
(iv) Survey equipment (GPS, Total Station, etc.); and
(v) A computer with MS Office, Datamine or Surpac and BMM Explorer (Assistant) Software.

1.3.1 Blast Movement Monitor (BMM®) Ball

The BMM® ball shown in Fig. 3 is made of Acrylonitrile-Butadiene-Styrene (ABS) plastic and contains a directional radio signal transmitter. It is a 98 mm diameter ball that is dropped in a dedicated non-blast hole within the blast pattern. BMM drill holes are normally planned between production holes (drilled holes for charging and blasting).

Two BMM®s are dropped in a hole but maximum of 4 could be installed in a hole. In the case of two balls, one is to measure the top flitch movement and the other the bottom flitch movement. It is worth mentioning that BMM® balls are not reusable.

Fig. 3 Blast Movement Monitor (BMM®) Balls (Anon., 2015)

1.3.2 BMM® Activator

The BMM® activator is a hand held remote control device that provides the signal not only to turn the transmitter on but also to assign a delayed start-up/transmission time. It is also used to quickly determine or test if a BMM® ball is transmitting signals. The BMM® activator consists of a tough ABS plastic case with a sealed low-profile keypad and supplied with a rubber boot for added protection. Fig. 4 shows the activator.

The following are parts of BMM® ball activator:
(i) Power button (black);
(ii) Set delay button (yellow);
(iii) BMM® activator (green);
(iv) Signal test on/off button (grey);
(v) Delay time (orange);
(vi) Transmit LED (green); and
(vii) Receive LED (red).

Fig. 4 Blast Movement Monitor (BMM®) Ball Activator (Anon., 2015)

1.3.3 GP5200 BMM® Detector

The GP5200 BMM® Detector shown in Fig. 5 is designed specifically to detect and interpret the signal produced by the BMM® balls. The GP5200 control box is water and dust resistant but should not be immersed in water since the charging socket is not waterproof. The detector continuously displays the signal strength and can quickly locate local peak signals of a transmitting BMM® ball. Local peaks occur directly above each BMM® ball and the signal strength is used to determine the depth of the BMM® ball and therefore its position in 3-dimensional space. The BMM® ball’s initial pre-blast position is recorded so a 3-dimension movement vector can be determined.

Fig. 5 Blast Movement Monitor (BMM®) Ball Detector (Anon., 2015)

1.3.4 Survey Equipment (GPS or Total Station)

BMM drill holes collar positions are surveyed using GPS or Total station before blasting. After blasting, the mining engineer knowing the approximate direction of the blast movement from the initiation sequence moves in that direction with the BMM® detector until the strongest signal from the BMM® ball is detected. The mining engineer then marks the position after recoding the signal and the surveyor determines the post blast coordinates of the BMM® ball's location on the muckpile.

1.3.5 Computer Software

All numerical calculations and analysis are performed on a computer. The following software are used for processing and analysing the data: MS Excel, BMM Explorer and Datamine or Surpac.

2 Resources and Methods Used

2.1 Materials

The study utilised secondary data from files and documents of AngloGold Ashanti, Iduapriem Mine. Primary data was also collected from field studies using BMM instrument at AAIL. Processing and analysis of data were done using BMM Explorer and Datamine Software also from the Mine.

The following are the summary of data used for the analysis:

(i) Blast movement monitoring data for twenty-two (22) months (April 2013 to January 2015) (about 117 data sets);
(ii) Twenty seven (27) blasts were monitored at Ajopa pit on four (4) different benches. All the data for the 27 shots were used for horizontal and vertical movement analysis; and
(iii) Four (4) shots (one from each bench) made up of 8 flitches out of the 27 shots monitored were considered in the cost-benefit analysis.

2.2 Methods

The BMM holes were measured to ascertain the depth of the holes and the BMM® balls were activated and placed into the drill holes. The BMM signal was then stored using the detector. After blasting, the post-blast BMM® positions in the muckpile were searched using the detector. Surveyors provided both the pre and post-blast BMM® coordinates.

The pre and post-blast data from the detector were downloaded into a computer. All the data were saved in .txt file format. The BMM Explorer software was provided with all the details of the blast such as:

(i) Blast ID;
(ii) Blast date;
(iii) Hole diameter (mm);
(iv) Bench height (m);
(v) Spacing and burden (m);
(vi) Delay timing (ms);
(vii) Powder factor (kg/m^3);
(viii) Type of explosive;
(ix) Type of initiation;
(x) Rock type;
(xi) Hole depth (m); and
(xii) Stemming length (m).

3 Results and Discussion

Shot "Blast_1607_20" is used as an example to illustrate results from the data collection. The shot properties listed from 1 to 12 in Section 2.2 were fed into the BMM Explorer software for rock movement analysis. Fig. 6 shows a window from the BMM Explorer software of the blast properties or input parameters of Shot 20 on 1607 Reduced Level (RL). Table 1 shows the summary of blast movement measurement of Shot 20. Fig. 7 shows the output of Shot 20, indicating the movement of the BMM® balls. Fig. 8 shows the plan view of horizontal movement of the BMM® balls. A total of eight (8) BMM® balls were placed in this pattern and all of them were detected after the blast. This shows 100% recovery. For the whole study average BMM® balls recovery was 96%.

Fig. 9 illustrates the vertical movement of Shot 20. Since there were two reefs in Shot 20, the center line for the shot was placed at the centre of the reefs hence the BMM®s from each reef could be seen moving towards each other as echelon (christmas tree) tie up was used. Blasting was done on 6 m bench and excavation was done in 3 m flitches. Two BMM® balls were dropped into a hole. The first BMM® ball was installed around 4.5 m depth for detecting the bottom flitch movement while the other BMM® ball was installed around 1.5 m depth (after back filling with stemming material) for monitoring the movement of the top flitch.

The entire Ajopa blast monitoring data were exported from the BMM Explorer into MS Excel for horizontal and vertical movement analysis. A scatter diagram was then plotted from the data set as shown in Fig. 10 and Fig. 11.

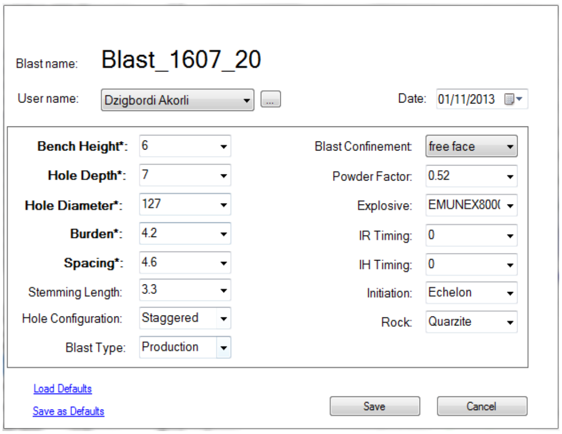

Fig. 6 Blast Properties from BMM Assistant Software

Table 1 Summary of the Blast Movement Measurement for Shot 20

BMM #	Initial Depth (m)	Horiz. Distance (m)	Vert. Distance (m)	3D Distance (m)	Direction (deg)	Inclination (m)	Initial Surface RL	Final Surface RL	Initial BMM RL	Final BMM RL	Post Blast Survey
1-G	4.0	2.7	1.3	2.9	42.8	25.3	1612.8	1615.1	1608.8	1610.1	B-G
2-R	1.5	2.0	2.1	2.9	45.9	46.2	1612.8	1615.1	1611.3	1613.4	A-R
3-O	4.2	2.1	0.2	2.1	38.7	5.3	1612.7	1613.8	1608.5	1608.7	D-O
4-Y	1.6	1.5	1.0	1.8	49.3	34.6	1612.7	1613.6	1611.1	1612.1	C-Y
5-G	4.5	4.3	1.1	4.4	345.9	14.6	1612.7	1614.9	1608.2	1609.3	E-G
6-O	1.5	5.5	3.8	6.7	345.1	34.7	1612.7	1613.8	1611.2	1613.4	F-O
7-R	4.4	3.2	0.3	3.2	356.4	5.9	1612.9	1614.3	1608.5	1608.8	H-R
8-O	1.4	2.6	1.0	2.8	348.8	21.4	1612.9	1614.0	1611.5	1612.5	G-O

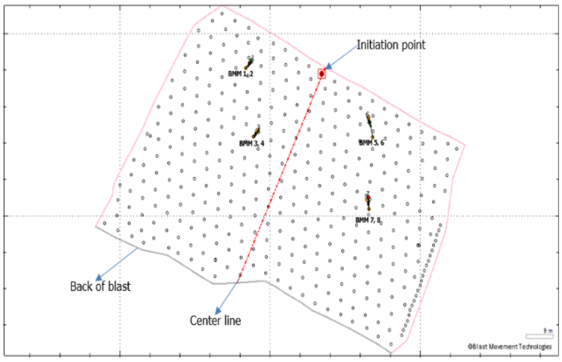

Fig. 7 Movement Vectors for Shot 20

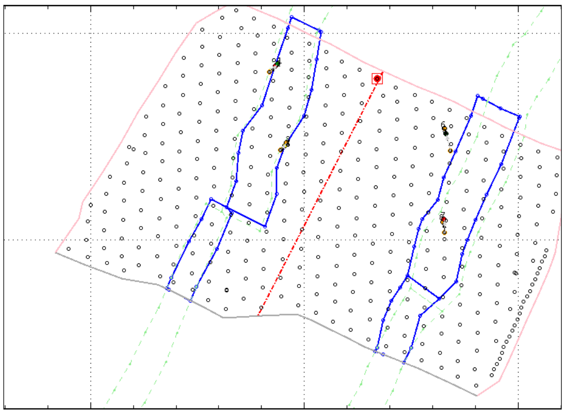

Fig. 8 Plan View of BMM® Balls in Drill Holes

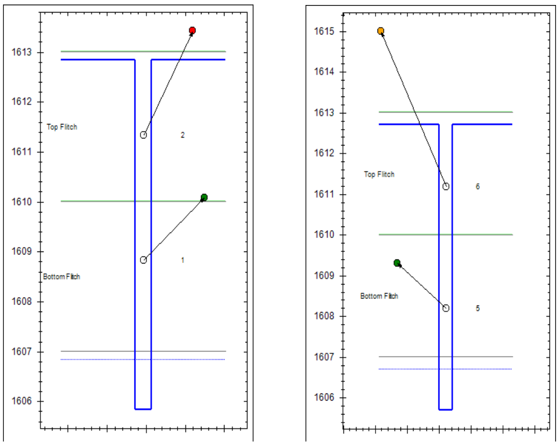

Fig. 9 Sectional View of BMM® Balls in Drill Holes

3.1 Horizontal Movement Analysis

A line of best fit was drawn through the scatter plots. A "D" shaped curve was observed indicating the bottom flitch moving farther than the top flitch. The average horizontal movement for bottom and top flitches were 3.0 m and 2.3 m respectively (see Fig. 10).

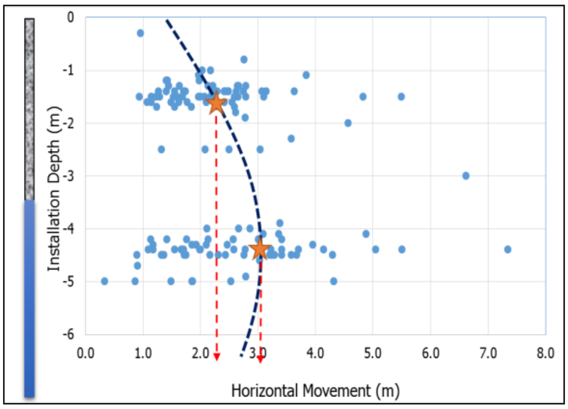

Fig. 10 Pictorial View of Horizontal Movement

3.2 Vertical Movement Analysis

Similar exercise was carried out for the vertical movement. A line of best fit was drawn through the points. It should be noted that the heave or vertical movement was calculated from the top of the bench i.e., for Shot 20, the top of the bench was 1613 RL, hence material above 1613 RL was classified as a heave. It could be observed that the top flitch moved higher than the bottom flitch. The average vertical movement for top and bottom flitches were 1.72 m and 0.9 m respectively (see Fig. 11).

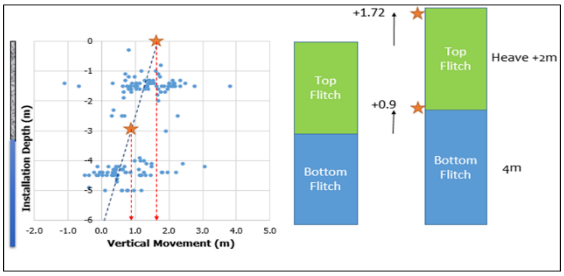

Fig. 11 Vertical Movement Interpretation (not drawn to scale)

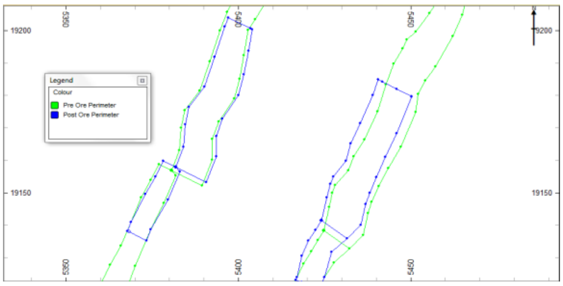

Fig. 12 Plan view of Pre and Post ore Perimeter Superimposed

3.3 Evaluating Ore Loss, Dilution and Misclassification

The adjusted perimeter was exported from BMM Explorer into Datamine and this was superimposed with the pre ore perimeter as shown in Fig. 12. Assuming the pre ore perimeter was used in mining without adjustment, there would have been ore loss, dilution and misclassification. The regions defining ore loss, dilution and misclassification are illustrated in Fig. 13.

Ore loss, dilution and misclassification perimeters were evaluated using BMM Explorer (See Fig. 14). The results were also confirmed using Datamine software. The orebody at Iduapriem Ajopa pit is homogeneous (i.e. variation in grade is not erratic along strike) hence misclassication was ignored in the cost-benefit analysis. Table 2 to 5 show the summary of evaluation of the eight flitches for the four (4) shots analysed.

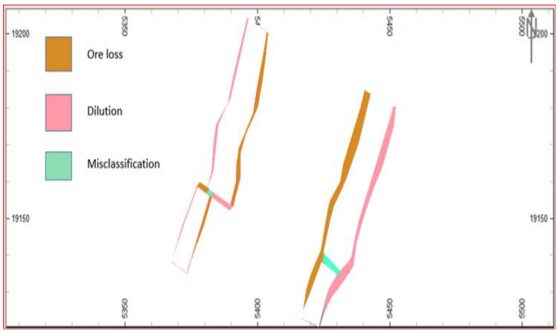

Fig. 13 Digitised Perimeters of Ore Loss, Dilution and Misclassification using Datamine Software

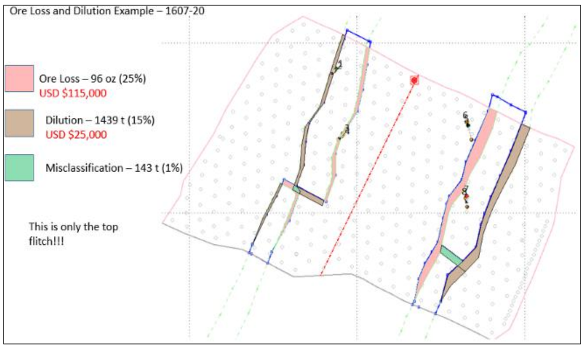

Fig. 14 Calculation of Ore Loss, Dilution and Misclassification using BMM Explorer

Table 2 Ore Loss and Dilution Summary (Blast_1607_20)

Blast_1607_20_Top_Flitch								
Block Name	***In Situ***		**Loss**		**Dilution**		**Misclassification**	
	(t)	**(g/t)**	**(t)**	(%)	**(t)**	(%)	**(t)**	(%)
Block_12_Top Flitch	1 010	1.62	376	37	159	16	0	0
Block_13_Top Flitch	3 919	1.24	1 285	33	795	20	119	3
Block_14_Top Flitch	1 129	1.09	417	37	72	6	0	0
Block_15_Top Flitch	3 713	1.16	446	12	413	11	24	1
Total/Weighted Average	**9 771**	**1.23**	**2 524**	**26**	**1439**	**15**	**143**	**1**
Blast_1607_20_Bottom_Flitch								
Block Name	***In Situ***		**Loss**		**Dilution**		**Misclassification**	
	(t)	**(g/t)**	**(t)**	(%)	**(t)**	(%)	**(t)**	(%)
Block_12_Bottom Flitch	1 010	1.62	342	34	151	15	0	0
Block_13_Bottom Flitch	3 919	1.24	1 136	29	700	18	143	4
Block_14_Bottom Flitch	1 121	1.09	432	39	64	6	0	0
Block_15_Bottom Flitch	3 721	1.16	479	13	485	13	40	1
Total/Weighted Average	**9 771**	**1.23**	**2 390**	**24**	**1399**	**14**	**183**	**2**

Table 3 Ore Loss and Dilution Summary (Blast_1601_13)

Blast_1601_13_Top								
Block Name	***In Situ***		**Loss**		**Dilution**		**Misclassification**	
	(t)	**(g/t)**	**(t)**	(%)	**(t)**	(%)	**(t)**	(%)
Block_11_Top Flitch	326	1.41	605	186	127	39	87	27
B lock_12_Top Flitch	2 457	1.12	780	32	501	20	0	0
Total/Weighted Average	**2 783**	**1.15**	**1 384**	**50**	**628**	**23**	**87**	**3**
Blast_1601_13_Bottom								
Block Name	***In Situ***		**Loss**		**Dilution**		**Misclassification**	
	(t)	**(g/t)**	**(t)**	(%)	**(t)**	(%)	**(t)**	(%)
Block_11_Bottom Flitch	318	1.41	180	56	95	30	167	53
Block_12_Bottom Flitch	2 441	1.12	1 032	42	644	26	0	0
Total/Weighted Average	**2 759**	**1.15**	**1 211**	**44**	**739**	**27**	**167**	**6**

Table 4 Ore Loss and Dilution Summary (Blast_1631_20)

Blast_1631_20_Top_Flitch								
Block Name	***In Situ***		**Loss**		**Dilution**		**Misclassification**	
	(t)	**(g/t)**	**(t)**	(%)	**(t)**	(%)	**(t)**	(%)
Block_11_Top Flitch	1 829	1.62	280	15	151	8	103	6
B lock_12_Top Flitch	3 021	1.62	208	7	215	7	0	0
Total/Weighted Average	**4 850**	**1.62**	**488**	**10**	**366**	**8**	**103**	**2**
Blast_1601_13_Bottom								
Block Name	***In Situ***		**Loss**		**Dilution**		**Misclassification**	
	(t)	**(g/t)**	**(t)**	(%)	**(t)**	(%)	**(t)**	(%)
Block_11_Bottom Flitch	1 836	1.62	281	15	143	8	175	10
Block_12_Bottom Flitch	3 156	1.62	176	6	366	12	8	0
Total/Weighted Average	**4 993**	**1.62**	**457**	**9**	**509**	**10**	**183**	**4**

Table 5 Ore Loss and Dilution Summary (Blast_1637_05)

Blast_1607_20_Top_Flitch								
Block Name	***In Situ***		**Loss**		**Dilution**		**Misclassification**	
	(t)	**(g/t)**	**(t)**	(%)	**(t)**	(%)	**(t)**	(%)
Block_13_Top Flitch	3 291	1.62	1 217	37	1010	31	32	1
Block_14_Top Flitch	3 514	1.62	901	26	938	27	0	0
Block_15_Top Flitch	56	1.62	0	0	0	0	0	0
Total/Weighted Average	**6 861**	**1.62**	**2118**	**31**	**1948**	**28**	**32**	**0**
Blast_1607_20_Bottom_Flitch								
Block Name	***In Situ***		**Loss**		**Dilution**		**Misclassification**	
	(t)	**(g/t)**	**(t)**	(%)	**(t)**	(%)	**(t)**	(%)
Block_13_Bottom Flitch	4 317	2.00	1 008	23	882	20	111	3
Block_14_Bottom Flitch	4 253	1.77	2 163	51	2 353	55	24	1
Block_15_Bottom Flitch	326	1.76	0	0	32	10	0	0
Total/Weighted Average	**8 896**	**1.88**	**3 171**	**36**	**3 267**	**37**	**135**	**2**
Grand Total/Weighted Average	**50 683**	**1.47**	**13 744**	**27**	**10 295**	**20**	**1 034**	**2**

3.4 Cost Benefit Analysis

Table 5 presents the total ore loss and dilution tonnages for the four (4) shots employed in the cost-benefit analysis while Table 6 outlines the estimation of the net revenue from employing the BMM system.

Assuming the monitoring was not carried out, the ore loss material would have been mined and sent to waste dump, but because of the BMM system, the material was "salvaged" to the ROM Pad. The revenue accrued from treating this material is estimated as $724 800. The differential cost incurred for moving the material to the ROM pad instead of waste dump is estimated as $9 621 using a differential unit cost of $0.7/t. Thus the benefit for salvaging the ore loss material by employing the BMM system is given by the revenue from the treated material less the differential cost which gives $715 179 as shown in Table 6.

Similarly, assuming the pre ore outline were used in mining, 10 295 t of diluted ore would have ended up at the processing plant thereby increasing the processing cost by $247 080 using a unit processing cost of $24/t. The revenue that would have been obtained for treating this material is estimated as $99 600 using the grade of the diluted ore as half of Ajopa pit low grade cut-off of 0.53 g/t i.e. 0.27 g/t. The cost saving for not transporting the material to the ROM pad for processing but moving the material to the waste dump is estimated as $7 207 using a unit differential cost of $0.7/t. Thus, the net revenue for not treating the diluted ore is given by the sum of the processing cost (which wasn't incurred thus a cost saving) and the differential cost saving of sending the material to the waste dump less the revenue that would have been obtained which gives $154 687 as presented in Table 6. The total revenue for employing the BMM system to cater for ore loss and dilution is estimated as $869 866 from the four (4) shots used for the analysis (see Table 6).

Table 7 shows the cost estimation input parameters for employing the BMM system for the four (4) shots used in the cost-benefit analysis. The total cost is estimated as $116 031 as shown in Table 8. With the net revenue estimated as $869 866 in Table 6, the net benefit for employing the BMM system using the four (4) shots for the analysis within the study period gives $753 835 which translates into a return on investment of 650%. The use of the BMM system is thus beneficial to the Mine even in terms of its financial implication.

Table 6 Net Revenue Estimation

Ore Loss							
Total Ore Loss (t)	**Grade (g/t)**	**Ounces (oz)**	**Recovery at 93% (oz)**	**Revenue @ $1 200/oz ($)**	**Differential Cost @ $0.7/t ($)**		**Net Revenue ($)**
13 744	1.47	650	604	+724 800	-9 621		+715 179
Dilution							
Total Diluted Ore (t)	**Grade (g/t)**	**Ounces (oz)**	**Recovery at 93% (oz)**	**Revenue @ $1 200/oz ($)**	**Differential Cost @ $0.7/t ($)**	**Processing Cost at $24/t ($)**	**Net Revenue ($)**
10 295	0.27	89	83	-99 600	+7 207	+247 080	+154 687
Total Net Revenue for Using BMM System							**$ 869 866**

Table 7 Cost Estimation Input Parameters

Inputs Parameters	**Unit Per Period**
Total Cost of Light Package BMM System	$ 114,490 /yr
Number of Blasts	4
Total Number of BMMs	26
Average No of Holes per Blast	3
Depth of Holes	4.5 m
Drilling Cost	$14.47 /m
Mining Engineer Labour Cost	$20 /hr
Surveyor Labour Cost	$20 /hr
Time to Install BMMs	2 hr /blast
Time to Detect BMMs	1.5 hr /blast
Time Spent by Surveyors	2 hr /blast
Number of Mining Engineers	2 /blast
Number of Surveyors	2 /blast
BMM Software	0.5 hr /blast

Table 8 Cost-Benefit Estimation

Total Cost of Monitoring and Adjusting 4 shots	
Total Annual Cost of Ownership (BMM System)	$114 490
Total Drilling Cost	$781
Total Mining Engineer Labour Cost	$600
Total Surveyor Labour Cost	$160
Total Cost (A)	**$116 031**
Net Revenue (B) (See Table 6**)**	**$869 866**
Net Benefit (C = B - A)	**$753 835**
Return on Investment (C/A * 100%)	**650%**

4 Conclusions and Recommendations

4.1 Conclusions

From the study and analysis, it can be concluded that:

(i) The average horizontal movement of the entire blast monitored at Ajopa is such that the bottom flitch of the blasts moved farther than the top; average bottom flitch movement was 3.0 m and average top flitch movment was 2.3 m.

(ii) The average vertical movement or the heave of the entire blast monitored is such that the top flitch of the blasts moved farther than the bottom flitch; average top flitch movement was 1.72 m and average bottom flitch movement was 0.9 m.

(iii) The cost of monitoring four (4) shots at Ajopa pit using the BMM system during the study period was $116 031 and the revenue was $869 866 which implies, Iduapriem Mine made a savings of $753 835 which amounted to 650 % Return on Investment (ROI).

(iv) Thus, the benefit of employing the BMM system at Iduapriem Mine has a positive financial implication.

4.2 Recommendations

(i) From the conclusions it is recommended that:

(ii) Implementation of the BMM system at Iduapriem Mine should be continued and if possible every shot containing ore should be monitored;

(iii) Dedicated team made up of at least two Engineers (Geological or/and Mining) should be trained specially for the task;

(iv) High precision GPS should be added to the detector instrument to make survey of pre and post BMM points easier and faster; and

(v) Finally, further research should be conducted which will consider sampling the ore loss and dilution regions within the muckpile to confirm the grades of these materials.

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