A STOCHASTIC APPROACH FOR DETERMINING THE RATIONAL PLACES FOR INSTALLING BLAST MOVEMENT MONITORING SENSORS IN THE BLASTING AREA

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ABSTRACT. This paper is grounded on the approach proposed by *Blast Movement Technologies* for tracking post-blast ore boundaries. Depending on the blast parameters of each blast and the place of each BMM® sensor, a different outcome of the movement vector can occur. Nevertheless, so far, post-blast ore boundaries have been calculated without taking into account the risk of using unrepresentative movement vectors. Therefore, this article attempts to quantify the risk of placing BMM® sensors based on the assessment of potential ore losses which can occur when digging in potentially incorrect post-blast ore boundaries. For this purpose, the average potential metal content in the excavated ore and its standard deviations are calculated in several considered cases for placing BMM® sensors. In addition, the Pareto frontier and the coefficient of variation approach are used for identifying the rational places for installing BMM® sensors.

Key words: blast movement monitoring, computer modelling, risk assessment, ore losses

СТОХАСТИЧЕН ПОДХОД ЗА ОПРЕДЕЛЯНЕ НА РАЦИОНАЛНИТЕ МЕСТОПОЛОЖЕНИЯ ЗА ПОСТАВЯНЕ НА ДАТЧИЦИ, ПРОСЛЕДЯВАЩИ ОТМЕСТВАНЕТО НА СКАЛАТА ПРИ ВЗРИВЯВАНЕ

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РЕЗЮМЕ. Настоящият материал се базира на подхода, въведен от *Blast Movement Technologies* за проследяване на отместването на минната маса при взривни работи. В зависимост от параметрите на взривните работи за всяко взривяване и местата на поставяне на BMM® датчици, могат да се наблюдават различни резултати за вектора на отместване. Независимо от това, до момента не е отчетен рискът получените резултати да бъдат неточни вследствие на това, че векторите на отместване не са представителни за взривяваното поле. Именно затова настоящият материал има за цел да даде количествена оценка на риска, който носи поставянето на BMM® датчик на определено местоположение, в зависимост от размера на потенциалните загуби и обедняване, които могат да се реализират при извършване на добивни работи в потенциално неправилни граници на рудните зони след взривяването. За тази цел се изчисляват средното очаквано количество метал, съдържащо се в добитата руда, и неговото стандартно отклонение за няколко разглеждани случая на възможни местоположения за датчиците. Като допълнение е използван метода на границата на Парето и коефициента на вариация за оценяване на рационалните места за поставянето на BMM® датчиците.

Ключови думи: проследяване отместване при взривяване, компютърно моделиране, оценка на риска, загуби на руда

Introduction

The problem of measuring blast movement has become topical as regards ore mining. Blast movement measurement has proved a far more reliable method than sole computer modelling or theoretical formulae. However, not many studies are focused on the topic of how BMM® (blast movement monitoring) sensors can provide unbiased or unrepresentative movement data, which can lead to distorted data and false estimations of the potential ore losses and dilution. This is a direct result of the unpredictable nature of the post-blast outcome in terms of precisely identifying the location of ore zones inside the muck pile. For this reason, the current article examines the possibility of establishing certain parameters in order to quantify the risk of obtaining unrepresentative or unreliable information from the BMM® sensors, while at the same time an attempt is made for locating the most suitable places for placing the sensors. Therefore, well-known theoretical and computer models can still be useful, but their application is strictly for estimating potential outcomes of the post-blast ore polygons locations in order to find the most suitable locations for placing the BMM®s and maximising the information gained from each BMM®. Nevertheless, after placing the BMM®s at the suggested locations, their actual movement should be tracked and recorded since the actual monitoring of blast movement is the most reliable way for obtaining information about the post-blast location of the ore.

Stochastic approach in blast movement monitoring

Following the assumption used by D. L. Taylor and I. R. Firth (2003) for quantifying the ore loss, ore misclassification, and ore dilution, based on a 2D model of the ore zones, this article also utilises this approach. The 2D model is also used in other case studies around mining sites around the world for several reasons:

1) Vertical dilution is difficult to quantify, as vertical movement vectors inside the blasting area are highly variable. The reason is that it is difficult to properly assume the vertical and horizontal vectors for certain segments of the bench, due to the variability of the rock type swelling factor inside the muck pile. However, a 3D approach to the problem is developed by Blast Movement Technologies and it is used for calculating evaded ore losses, dilution, and misclassification in a 3D environment (https://blastmovement.com/). Nonetheless, it is not well established whether this approach provides more accurate results due to the assumptions made both in the 2D and 3D model.

2) Computational time required for calculating the estimates of the ore loss, ore misclassification, and ore dilution volumes in a 2D model is generally less than in a 3D environment;

3) Results from applying a model for the random outcomes of a process, such as blasting, are not ideal, but a 2D approach is far simpler for getting a general idea of what to expect of the approximate location of the ore inside the muck pile. Furthermore, in many cases, horizontal movement exhibits a good linear correlation with the 3D movement. This can derive from the high values of the coefficient of determination between the magnitude of the horizontal movement vector and the magnitude of the 3D movement vector ($R^2>0.90$) (Zhi Yu et al., 2020; Zhi Yu et al., 2021). In contrast, the vertical movement component has a relatively weak correlation to the 3D movement vector and, therefore, their relation is not apparent.

These arguments reinforce the validity of the 2D approach for considering horizontal movement instead of the 3D movement approach to identify the locations of the post-blast ore volumes. However, one should know that this approach is not ideal, but it allows mining engineers to establish a guideline for shovelling operations.

Case study

General idea

In a previous case study, it was established that Ore Polygon 1 (red) and Ore Polygon 2 (green) are the ones with higher priority for tracking. However, it is still unknown where exactly the BMM® sensors should be placed in order to gain maximum unbiased information from their post-blast measurement. Therefore, three cases for BMM® location placement are considered for comparison (Fig. 1, 2, and 3).

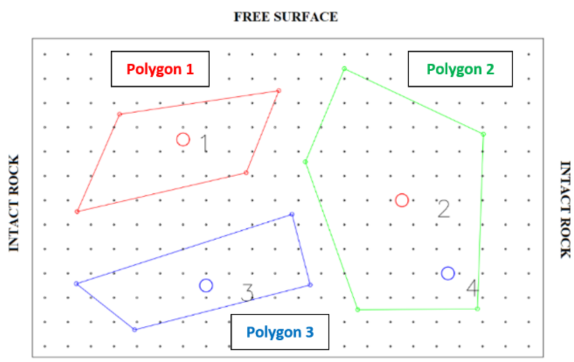

Fig. 1. BMM® locations – case 1

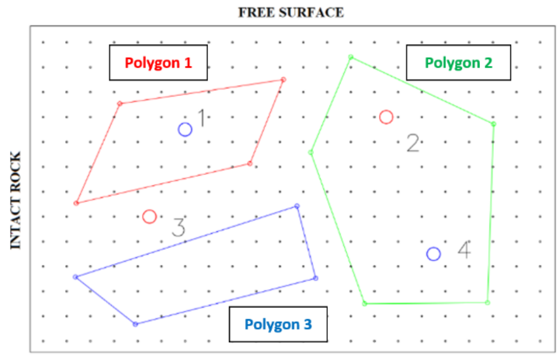

Fig.2. BMM® locations – case 2

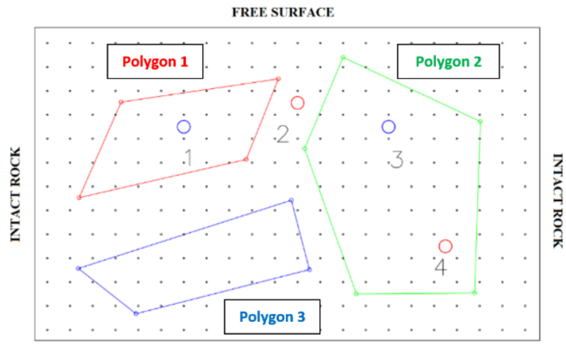

Fig.3. BMM® locations – case 3

Due to the immensely large number of outcomes which can be generated for each BMM® location following the law of distribution for the horizontal movement vector magnitude, a simpler approach is needed, rather than generating hundreds of vector outcomes. It can be calculated that the number of cases which need to be considered grows exponentially, depending on the number of BMM® locations considered. Therefore, we propose that three conditions should be examined for the horizontal movement vector for each BMM® – the minimum (R_{min}), the average ($\bar{R}$), and the maximum distance (R_{max}). All of the above parameters can be taken from the site measurements or they can be taken from computer-generated data which are normally distributed, given that the vector magnitude is normally distributed. In many cases the vector magnitude indeed obeys a normal distribution law (Harris et al., 2001; Engman, 2013; Isaaks et al., 2014; Hunt and Thornton, 2014). Furthermore, it is widely proven that the general direction of movement of the BMM® sensors is approximately perpendicular to the isochrones in the blasting pattern. However, due to the random nature of the movement vector, these cases need to be considered for the angle deviation: ± maximum angle deviation and direction perpendicular to the isochrones (average expected direction). Therefore, there are a total of 9 outcomes for the horizontal movement vector of each BMM® sensor, following this approach. Given that 4 BMM® sensors are placed in the blasting panel, a total of $9^4 = 6561$ vector combinations (and polygon outcomes) can be established. Given that 3 cases are considered, a total of more than 387 million polygon comparisons are processed. Any additional case or BMM® location will dramatically increase the total number of polygon comparisons exceeding 1 billion cases. Figure 4 represents the concept of generating the boundaries of the moved ore polygons, based on the possible outcomes for the movement vector. The common area between e.g. the green and blue polygon (these colours apply for Fig. 4) is the potential area where no losses would occur, given that the blue polygon is the actual post-blast boundary and the green polygon is a predicted one. The opposite case is also valid, where the green polygon is the actual post-blast polygon and the blue one is a simulated one. Following the approach used by Blast Movement Technologies, the area outside the common area is either the potential ore lost due to shovelling in the wrong boundaries, or the waste which dilutes the ore.

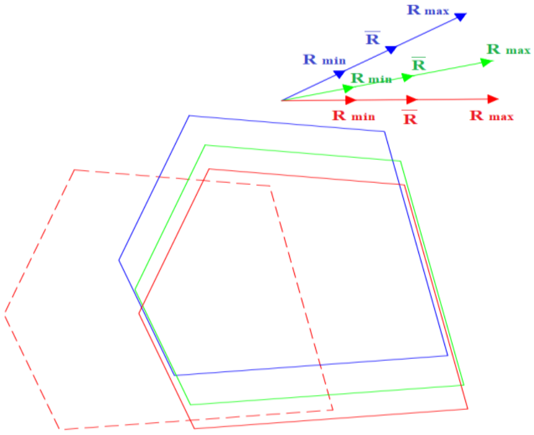

Fig.4. Possible outcomes for the blast movement of the ore polygons

Provided that a blast panel has more than one BMM® placed in different locations, each one has its influence on the ore polygon movement. For this research, the simple technique of ID^2 (the inversed distance squared), proposed by Taylor and Firth (2003), is used for obtaining the weights for each BMM® location for the different points from the ore polygons. Other techniques can also be applied, such as Polynomial Surface fit, Triangulation, Kriging, etc., as mentioned by Taylor and Firth (2003). However, the study of which approximating technique is better is not a scope of this article. In addition, Taylor and Firth (2003) have proven that the ID^2 method provides practical results. In this article, the considered method is used only to "bootstrap" the assessment model and illustrate the importance of the BMM® sensor locations for the end-result.

After the locations of the simulated post-blast ore polygons are established, the calculation of the potentially avoided ore losses and ore dilution are done by calculating the intersecting areas of the pre-blast and post-blast polygons.

After that a matrix is drawn for each ore polygon. Therein, the rows are the generated iterations for the displacement of Ore Polygon 1 (OP 1) in BMM® Locations - case 1, while the columns represent the possible outcomes for the same Ore Polygon 1 from all the other post-blast BMM® Locations in cases 2 and 3.

In this study, we assume that each case of blast movement can potentially be the actual ore polygon movement, regardless of whether it is monitored by BMM® sensors or not. This provides the possibility of establishing a matrix where each polygon outcome is compared with all the generated polygon outcomes, assuming each one of them could be the actual movement. The purpose of these matrices is to evaluate the potential extracted metal (EM) in the ore before processing in the considered cases, assuming the rows of iterations for the polygon displacement are the ones which the BMM® sensors would generate in a field study.

Therefore, this approach attempts to quantify the risk of realising unnecessary ore losses which derive from the uncertain information that the BMM® sensors provide, based on their installation location.

Hence, comparing every row of iterations from BMM® Locations – case 1 with all the iterations from BMM® Locations - cases 2 and 3 would give the possibility to quantify the potential extracted metal, given that every other iteration from BMM® locations 2 and 3 are the actual displacements. The same logic can be applied for cases 2 and 3. To sum up, this approach provides information about the extracted metal which occurs in different cases, when shovelling is done in the assumed boundaries, which either happens to be in the correct, or the incorrect post-blast boundaries. Tables 1, 2, and 3 represent the general idea behind the matrices.

Table 1. *Comparison matrix for Case 1*

SIMULATED BMM® MEASUREMENTS Ore Polygon 1 (generated from case 1)					
			OP_{11n}	**…**	**OP_{11n}**
ASSUMED ORE POLYGON DISPLACEMENT	**BMM® Locations case 2**	**OP_{211}**	$EM_{111-211}$	…	$EM_{11n-211}$
		OP_{212}	$EM_{111-212}$	…	$EM_{11n-212}$
		…	…	…	…
		OP_{21i}	$EM_{111-21i}$	…	$EM_{11n-21i}$
		…	…	…	…
		OP_{21n}	$EM_{111-21n}$	…	$EM_{11n-21n}$
	BMM® Locations case 3	**OP_{311}**	$EM_{111-311}$	…	$EM_{11n-311}$
		OP_{312}	$EM_{111-312}$	…	$EM_{11n-312}$
		…	…	…	…
		OP_{31i}	$EM_{111-31i}$	…	$EM_{11n-31i}$
		…	…	…	…
		OP_{31n}	$EM_{111-31n}$	…	$EM_{11n-31n}$

Table 2. *Comparison matrix for Case 2*

SIMULATED BMM® MEASUREMENTS Ore Polygon 1 (generated from case 2)					
			OP_{211}	**…**	**OP_{21n}**
ASSUMED ORE POLYGON DISPLACEMENT	**BMM® Locations case 1**	**OP_{111}**	$EM_{211-111}$	…	$EM_{21n-111}$
		OP_{112}	$EM_{211-112}$	…	$EM_{21n-112}$
		…	…	…	…
		OP_{11i}	$EM_{211-11i}$	…	$EM_{21n-11i}$
		…	…	…	…
		OP_{11n}	$EM_{211-11n}$	…	$EM_{21n-11n}$
	BMM® Locations case 3	**OP_{311}**	$EM_{211-311}$	…	$EM_{21n-311}$
		OP_{312}	$EM_{211-312}$	…	$EM_{21n-312}$
		…	…	…	…
		OP_{31i}	$EM_{211-31i}$	…	$EM_{21n-31i}$
		…	…	…	…
		OP_{31n}	$EM_{211-31n}$	…	$EM_{21n-31n}$

The same principles can be applied for the matrices for Ore Polygons 2 and 3.

The average extracted metal (AEM) represents the magnitude of avoided losses due to dilution and ore losses, which derive from shovelling in the incorrect boundaries, while the standard deviation of the extracted metal values represent the uncertainty of the information obtained from the BMM® sensors in their respective locations for the considered case.

Table 3. *Comparison matrix for Case 3*

SIMULATED BMM® MEASUREMENTS Ore Polygon 1 (generated from case 3)					
			OP_{311}	…	OP_{31n}
ASSUMED ORE POLYGON DISPLACEMENT	BMM® Locations case 1	OP_{111}	$EM_{311-111}$	…	$EM_{31n-111}$
		OP_{112}	$EM_{311-112}$	…	$EM_{31n-112}$
		…	…	…	…
		OP_{11i}	$EM_{311-11i}$	…	$EM_{31n-11i}$
		…	…	…	…
		OP_{11n}	$EM_{311-11n}$	…	$EM_{31n-11n}$
	BMM® Locations case 2	OP_{211}	$EM_{311-211}$	…	$EM_{31n-211}$
		OP_{212}	$EM_{311-212}$	…	$EM_{31n-212}$
		…	…	…	…
		OP_{21i}	$EM_{311-21i}$	…	$EM_{31n-21i}$
		…	…	…	…
		OP_{21n}	$EM_{311-21n}$	…	$EM_{31n-21n}$

This uncertainty can also be interpreted as the risk of obtaining unrepresentative or unreliable information from the BMM® sensors, which derives from the highly deviating results in their particular location. The lower the magnitude of the extracted metal and the bigger the uncertainty for the considered location, the more unwise it is to place the BMM® sensors in the manner considered.

The average of all the values for the metal contained for all the ore polygons in the considered cases for BMM® locations is given in Table 4 below:

Table 4. *General results for the considered cases*

	BMM® locations Case 1	BMM® locations Case 2	BMM® locations Case 3
Ore Polygon 1	AEM_{11}, σ_{11}	AEM_{21}, σ_{21}	AEM_{31}, σ_{31}
Ore Polygon 2	AEM_{12}, σ_{12}	AEM_{22}, σ_{22}	AEM_{32}, σ_{32}
Ore Polygon 3	AEM_{13}, σ_{13}	AEM_{23}, σ_{23}	AEM_{33}, σ_{33}
Overall results for current shot	AEM_1, σ_{EM1}	AEM_2, σ_{EM2}	AEM_3, σ_{EM3}

The standard deviation of the potential extracted metal (σ_{EM}) for BMM® locations 1 is calculated for all the values of the extracted metal from Tables 1, 2 and 3. The same is applied for BMM® locations 2 and 3. The average extracted metal values and the standard deviations for the three cases are represented in a coordinate system, where the two axes are AEM, σ_{EM}. This approach is applied in order to find the Pareto-optimal solutions and exclude all the non-dominant ones. If no Pareto-optimal solution is found, the risk/reward approach is applied by using the variation coefficient.

Input data

Table 5 represents the input data regarding the movement vectors for each installed BMM®. Each BMM® maximum, minimum, and average movement data have been artificially generated for this case study. The angle deviation is taken from field studies.

Table 5. *Input values for all considered cases*

CASE 1				
	$\bar{R}$,m	R_{min} ,m	R_{max},m	Angle deviation, °
BMM® 1	2.12	1.98	2.54	± 20°
BMM® 2	2.26	2.08	2.67	± 20°
BMM® 3	1.77	1.43	2.04	± 20°
BMM® 4	1.61	1.32	1.94	± 20°
CASE 2				
	$\bar{R}$,m	R_{min},m	R_{max},m	Angle deviation, °
BMM® 1	2.12	1.98	2.54	± 20°
BMM® 2	2.26	2.08	2.67	± 20°
BMM® 3	1.77	1.43	2.04	± 20°
BMM® 4	1.61	1.32	1.94	± 20°
CASE 3				
	$\bar{R}$,m	R_{min},m	R_{max},m	Angle deviation, °
BMM® 1	2.12	1.98	2.54	± 20°
BMM® 2	2.35	2.04	2.57	± 20°
BMM® 3	1.98	1.75	2.21	± 20°
BMM® 4	1.61	1.32	1.94	± 20°

The bench height for this case study is 5m, where only 1 BMM® is placed per drill hole. The rock density is:

ρ = 2.3 t/m³

The grades for the three ore polygons are as follows:

- Ore Polygon 1 (blue) – low grade;
- Ore Polygon 2 (green) – medium grade;
- Ore Polygon 3 (red) – very high grade.

The firing pattern is an echelon, where the blast holes are drilled in a square pattern. For this shot, the overall blast movement direction is NE.

Results

The results from the statistical analysis from the generated data are represented in Table 6 and in Fig. 5.

Table 6. *Output values for all considered cases*

BMM® locations. CASE 1	
Ore Polygon 1 (blue)	AEM_{11} = 2802.03 σ_{11} = 36.72
Ore Polygon 2 (green)	AEM_{12} = 16 740.65 σ_{12} = 185.29
Ore Polygon 3 (red)	AEM_{13} = 17 388.50 σ_{13} = 378.57
Overall results for current shot	**AEM_1 = 36 931.17** **σ_{EM1} = 423.08** **Variation = 1.15 %**

BMM® locations. CASE 2	
Ore Polygon 1 (blue)	AEM_{21} = 2812.78 σ_{21} = 37.41
Ore Polygon 2 (green)	AEM_{22} = 16 761.05 σ_{22} = 187.75
Ore Polygon 3 (red)	AEM_{23} = 17 414.74 σ_{23} = 367.39
Overall results for current shot	**AEM_2 = 36 988.58** **σ_{EM2} = 414.28** **Variation = 1.12 %**
BMM® locations. CASE 3	
Ore Polygon 1 (blue)	AEM_{31} = 2806.47 σ_{31} = 36.73
Ore Polygon 2 (green)	AEM_{32} = 16 790.97 σ_{32} = 188.54
Ore Polygon 3 (red)	AEM_{33} = 17 410.93 σ_{33} = 384.01
Overall results for current shot	**AEM_3 = 37 008.38** **σ_{EM3} = 429.38** **Variation = 1.16%**

It is noticeable that Case 2 is more favourable than Case 1 in terms of average expected excavated ore tones, as well as due to the lower value for the standard deviation (the risk value). From the standpoint of the Pareto-frontier problem, Case 2 dominates over Case 1. However, Case 3 provides an additional 19.8 g of averagely expected metal contained in the excavated ore, which is obtainable at an increase of the risk value by 3.6 %. Both the additional reward and its additional risk taken for Case 3, compared to Case 2, are relatively low. Following the logic of the risk/reward ratio approach, calculating the variation coefficient for the considered cases shows that the lowest ratio goes to Case 2, while the highest ratio is for Case 3. The same logic can be interpreted from Fig. 5.

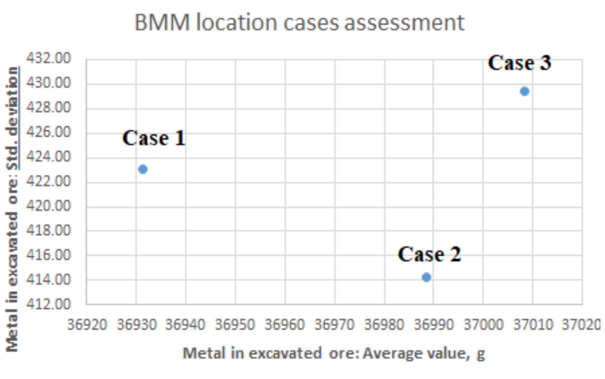

Fig.5. BMM® location cases assessment

Therefore, it is rational to install the BMM® sensor according to the locations in Case 2, as the risk is the lowest, while at the same time, the average expected “reward” is close in terms of values to the case with the highest possible average “reward”.

Conclusions

Several important conclusions can be drawn from this case study:

1) Given that the law of distribution can be established for the movement vector magnitude, while at the same time the maximum and minimum angle deviation for the same vector is observed, 9 of the most important possible occurrences of the movement vector can be established.

2) This approach can be applied in an individual manner according to the location of the BMM® sensor from the free face, which provides an individual range for each of the studied BMM® sensor locations.

3) The use of the computer-generated polygons from the vector combinations regarding all locations and all cases provide a matrix for each polygon and case, where the risk of shovelling in the incorrect dig lines can be established. At the same time, the average expected excavated metal contained in the excavated ore can be calculated for each polygon and for each case as an overall sum.

4) The Pareto-frontier approach, as well as the risk/reward ratio approach using the variation coefficient, can prove to be useful tools for solving the search for a rational BMM® location problem.

Further studies

The following case study illustrates this approach in one of the simplest cases, where all ore polygons are isolated. In order to establish a universally working model, neighbouring ore polygons have to be introduced in order to include misclassification volumes in the model. In addition, more cases have to be considered in future for comparison, while maintaining the total number of considered cases to a minimum. An optimisation is needed for the comparison algorithm to further reduce computational time.

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