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BLAST MOVEMENT MONITORING IN GRADE CONTROL OF ZHAIREM MINESITE CONSIDERING ORE LOSSES AND DILUTION

Abstract

This paper examines the economic efficiency of Blast Movement Monitors (BMMs) in a grade control environment within open-pit mining operations. Blast-induced displacement of ore-waste contacts remain a major constraint on effective grade control in open-pit mining. Unaccounted movement during blasting frequently leads to ore dilution, loss of valuable material, and misclassification, ultimately reducing processing efficiency and economic returns. The study is based on the premise that blast-induced rock mass movement is inherently stochastic and cannot be reliably reproduced using deterministic modelling alone; therefore, high-precision grade control requires direct in-situ measurement. By capturing three-dimensional displacement vectors from multiple monitoring points within a blast block, BMM enables more accurate reconstruction of post-blast ore boundaries. This multi-point approach accounts for spatial variability and provides a robust basis for updating polygons prior to excavation. In 2024, the pilot implementation of the BMM system was started at the Zhairem Mining and Concentrating Complex (MCC), and the system is being implemented at several Kazakhstan mining companies. Using field data from the Zhairem site, the study quantifies the operational consequences of uncontrolled blast movement, including ore loss, dilution, and misclassification. The results indicate that improved boundary delineation enhances resource utilisation and contributes directly to increased profitability. Based on these findings, the paper proposes a financial value assessment tool designed to support investment decisions related to blast movement monitoring systems, enabling operations to systematically evaluate the cost–benefit ratio of BMM implementation and optimise grade control strategies within a broader economic framework.

Keywords: Blast Movement Monitors, grade control, ore loss, dilution, misclassification, ROI, Zhairem, Kazzinc, Glencore, ore, open-pit, zinc, barite, mineralisation type, excavation.

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Introduction

Minesite profits are significantly impacted by throughput and cost efficiency of the comminution process, starting with 'Drill and Blast'. Fragmenting rock with explosives is substantially cheaper per tonne than size reduction in the plant, so optimising drill-and-blast is one of the largest levers for improving economic performance [1–2]. Blasting outcomes also affect downstream unit operations, affecting excavation, haulage, and mill performance [1–3]. It is therefore essential not only to design effective blasts, but also to measure and understand their impacts on both rock fragmentation and ore-waste spatial relationships.

Grade control aims to maximise ore recovery and minimise waste processing in plant. In open pit operations, ore-waste boundaries are typically defined using resource models based on diamond core and RC drilling, then refined with blast-hole sampling [4–5]. However, the initial step of the comminution chain, production blasting – induces complex, highly variable rock movement that displaces these ore-waste contacts [6]. If the post-blast movement is not accounted for, ore is sent to the waste dump (ore loss), waste is sent to the plant (dilution), or material is routed to suboptimal destinations (misclassification). Case studies from large gold operations report ore misclassification of 3-8% and theoretical ore losses of 9–24%, with multi-million-dollar impacts on project value depending on orebody geometry and blast conditions [6–7].

In parallel with a robust grade control system, BMM data enables the derivation of corrected post-blast dig polygons, reducing ore loss and dilution and improving reconciliation and project profitability [8–9]. Despite demonstrated technical benefits and reported returns on investment, the adoption of BMMs is often constrained by perceptions of cost and operational complexity. This study presents a comprehensive analysis of the economic efficiency of BMM implementation in grade control, quantifying costs and benefits under different geological and operational scenarios and identifying conditions under which BMMs deliver the greatest economic value.

Scientific contribution

This study provides several contributions to the existing body of knowledge in grade control and blast movement analysis:

1. It establishes a direct quantitative link between blast-induced displacement and economic performance, enabling the evaluation of ore loss, dilution, and misclassification in monetary terms.
2. It introduces misclassification as an independent economic category, particularly relevant for polymetallic deposits with multiple processing streams, where conventional approaches tend to aggregate this effect within dilution.
3. It explains a practical value-based framework for decision-making, allowing mining operations to assess the return on investment (ROI) of BMM systems under varying geological and economic conditions.

Materials and methods

The study demonstrates first use of BMM technology in a geologically complex polymetallic deposit in Kazakhstan, where multiple ore types with different economic values and processing routes coexist. This enables the explicit consideration of misclassification as a separate economic category, which is often overlooked in conventional grade control assessments. Although based on a case study, the proposed workflow provides a practical framework for linking blast-induced displacement with value-based decision-making in open-pit mining.

Understanding the Zhairem Deposit

One of the key technical challenges in contemporary open-pit mining, especially at structurally complex deposits such as the Zhairem Mining and Processing Complex (MCC), is achieving alignment between planned ore grades and the material that ultimately reaches the processing plant. A major source of this mismatch is the uncontrolled movement of ore-waste boundaries and contacts between different ore types during blasting operations. The goal of the Blast Movement Monitoring (BMM) system is to provide a direct means of tracking this displacement.

The core issue lies in the fact that displacement within a blast block is neither uniform nor easily predictable. Field experience indicates that the movement vector varies significantly and is governed by numerous interacting factors, including blast design parameters, geomechanical characteristics of the rock mass, and surrounding rock conditions. This simplified approach does not reflect the spatial heterogeneity of blast-induced displacement, which published studies [10–13] have shown may deviate from average horizontal movement values by as much as ±50%. Moreover, displacement direction can vary unpredictably, further limiting the reliability of extrapolation from limited measurements.

The precision requirements of modern grade control, often targeting boundary definition within ±0.2 m cannot be consistently achieved through predictive simulation alone. Many mine sites have High Precision Systems on excavators to accurately dig to plan. Despite continuous improvements in both hardware and computational tools, blast modelling remains insufficiently representative for detailed contact delineation. This limitation stems primarily from uncertainties in input parameters (such as in-situ rock mass properties) and from the simplifying assumptions embedded in numerical algorithms, which cannot fully reproduce the complex, dynamic processes occurring during full-scale blasting. Practical observations repeatedly demonstrate a marked discrepancy between modelled forecasts and displacement data obtained from BMM systems.

Hexagon’s Blast Movement Monitoring (BMM) system comprises:

- Blast Movement Monitors, radio-frequency sensors installed in dedicated holes prior to firing
- Handheld detector to locate the post-blast BMM positions
- Software that computes movement vectors and translates ore/waste polygons to their true post-blast locations.

The system is used to reduce ore loss, dilution and misclassification by redefining dig boundaries based on measured movement, thereby increasing ore recovery and economic performance.

Workflow:

- BMMs are activated and installed in the blast pattern, typically at ore-waste boundaries or other key locations.
- After blasting, the BMMs are detected on the muckpile surface using a handheld detector.
- The pre and post-blast positions are compared to generate a movement vector.
- These vectors are input into software (BMM Explorer), which translates the ore and waste boundaries to their true post-blast locations.
- Updated dig polygons are provided to the mining team, ensuring that ore is sent to the mill and waste to the dump, as intended.

Value Calculator

The Value Calculator transforms physical movement into economic metrics. For each category, the net value is computed from recoverable metal revenue less mining and processing costs. The calculator uses block-by-block data (tonnage, grades, costs, recovery, prices) to estimate the net value impact for each category.

Definitions:

- Ore Loss – The rock mass that has moved outside the original ore boundary because of blasting (Figure 1).

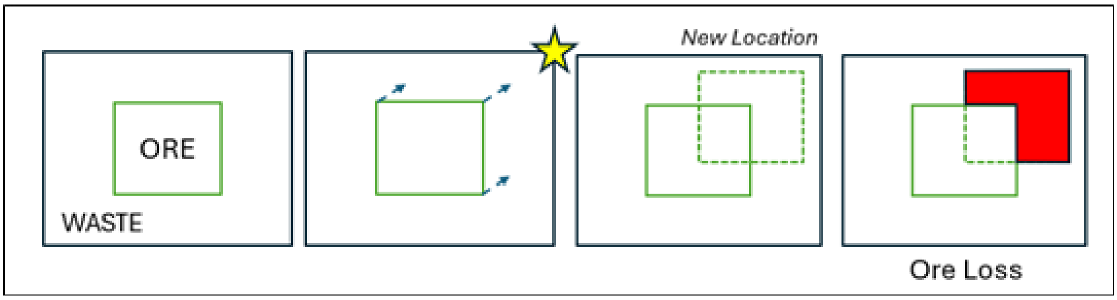

Figure 1 – A visual representaion of 'Ore Loss' (marked red)

- Dilution – Waste rock mass that has moved inside the original ore boundary because of blasting. (Figure 2)

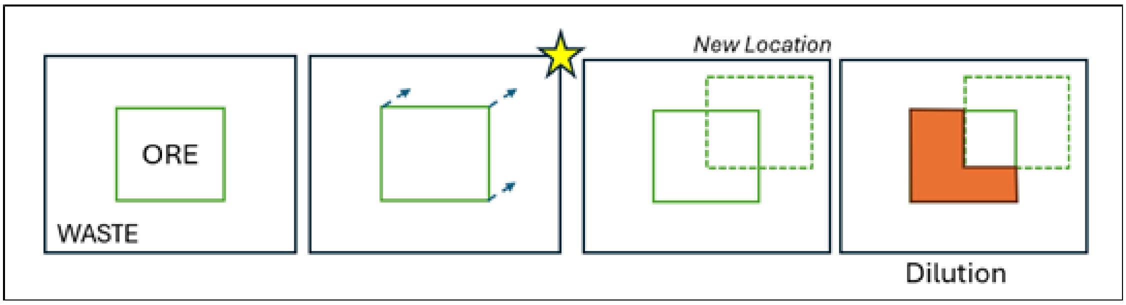

Figure 2 – A visual representation of 'Dilution' (marked brown)

- Misclassification – Ore or waste that is incorrectly classified, leading to suboptimal processing or disposal (Figure 3).

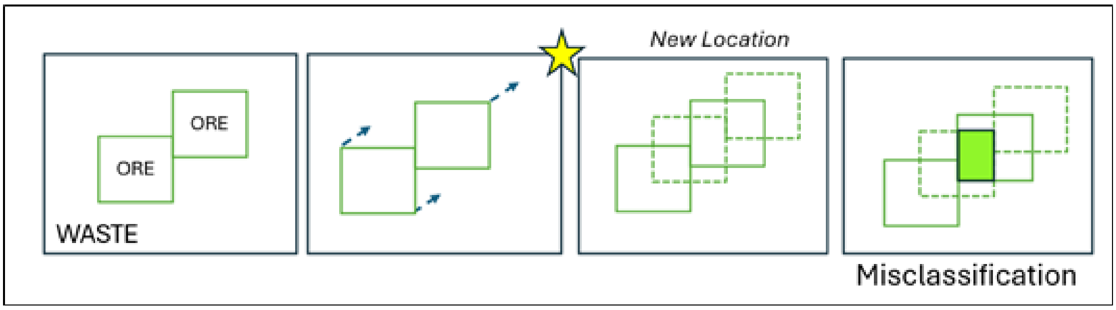

Figure 3 – A visual representation of 'Misclassification' (marked green)

- Grade (%) – Percentage of valuable material (ore) within the rock mass.
- Example: 100t of ore @ with a grade of 2 grams/tonne would contain 200 grams of ore.
- Recovery (%) – Percentage of valuable material recovered during the metallurgical processing stage.
- Example: A processing plant with 90% efficiency was fed 100t of ore @ with a grade of 2 grams/tonne. Only 90% of the material (180 grams) would be extracted from the rock mass. The remaining 20 grams would become tailings.
- Processing Cost ($) – The milling unit cost (USD $/ton) represents the total expense to process one tonne of ore through the plant. Only ore tonnes are considered.
- Mining Cost ($) – The total expense incurred to move one tonne of material (both ore and waste) in the open pit.

Calculating Ore Loss

As mentioned above, Ore Loss is the (high value) ore blocks that have moved outside the original ore boundary during blasting. This material is sent to the waste dump. Ore loss is represented in several ways.

- Ore Loss (t) – The weight of material that has moved outside of the original ore block.
- Ore Loss (%) – Tonnage of material outside the original ore block / the total tonnage of the ore block * 100.
- Ore Loss ($) – The value of the ore lost is calculated, then the mining and processing cost is subtracted from the total. Even though this material is treated as waste, the processing cost is still attributed to the value of the ore.

$$[\text{Ore Loss} \times \text{Grade} \times \text{Recovery} \times \text{Price})] - [(\text{Ore Loss} \times \text{Mining Cost}) + (\text{Ore Loss} \times \text{Processing Cost})]$$

Calculating Dilution

When the blast occurs, waste material can move inside the original ore boundary. If site was not to account for blast movement, and mined insitu, the waste material would be processed as ore. Despite having no economic value, it is treated as ore and incurs additional economic harm.

- Dilution (t) – Weight of waste material (tonnes) that has moved inside the original ore boundary.
- Dilution (%) – Tonnage of material that has moved inside the original ore boundary / the total tonnage of waste in the blast * 100.
- Dilution ($) – The cost to mine and process material that has no economic value.

$$[\text{Dilution (t)} \times (\text{Mining Cost})] + [\text{Dilution (t)} \times (\text{Processing Cost})]$$

Calculating Misclassification

When the blast occurs, ore may move into another ore block. In some cases, this may be okay (i.e. a low value material moving into a high value ore block. However, in other situations this can have a significant financial impact, particularly when these materials are processed different ways. As an example, in iron ore mines, sites can have ore bodies with high sulphur or phosphorus can have significant downstream effects. This can affect the quality of the steel product and may involve penalties for the company for providing an out of spec raw material.

Zhairem Mine Site (Kazzinc/Glencore)

Zhairem is one of the largest polymetallic deposits in Kazakhstan, hosting substantial zinc-lead, barite-polymetallic and iron-manganese ore reserves in the Ulytau Region near the settlement of Zhairem. The mining and processing complex is operated by Kazzinc, in which Glencore International AG is a shareholder. Zhairem forms part of the Atasu ore district and is a major iron-manganese ore field situated within the Zhailma volcano-tectonic depression, a Devonian graben-syncline whose structure and magmatism strongly control ore formation and mining conditions [14]. The operating area includes the Zapadny, Dalnezapadny and Eastern Zhairem deposits, characterised by complex geology and hydrogeology that are critical for exploration strategies, slope stability and mine drainage design [14–15]. Currently, open-pit mining is conducted only at the Dalnezapadny pit [15]. The reserves of the Zhairem deposit recorded on the state balance sheet are classified by mineralisation types:

- In the Dalnezapadny pit:
- Oxidised polymetallic type;
- Sulfide polymetallic type;
- Oxidised barite-polymetallic type;
- Sulfide barite-polymetallic type;
- Barite type.

Table 1 – Mineralisation Types of Dalnezapadny pit

No.	WEATH/FRESH	$BaSO_4$	ZnEq	Mineralisation Types	Mineralisation Type Code
1	Fresh	< 40	≥ 1	Sulfide polymetallic	LBS
2	Weathered	≥ 40	≥ 1	Oxidised barite-polymetallic	HBO
3	Weathered	< 40	≥ 1	Oxidised polymetallic	LBO
4	Fresh	≥ 40	≥ 1	Sulfide barite-polymetallic	HBS
5	–	≥ 40	$0.01 < ZnEq < 1$	Barite	MONOBA
6	otherwise			Waste rock	WASTE

- Formula of Zinc Equivalent (ZnEq) : $ZnEq = (11.45*Zn) + (7.32*Pb) + (0.42*Ag)$.
- Grade of Barite : $BaSO_4$
- WEATH/FRESH – spatial position of waste/ore bodies relative to the boundary of the weathering (oxidation) zone.

Blast 220-6

Blast 220-6 was a V-pattern shot fired toward a free face with five BMMs installed. Blast Parameters are listed in Table 2. A plan view of the blast is shown in Figure 4, displaying the blast holes, centreline, initiation point (IP) and timing contours. 253 Blast holes were drilled, along with 5 BMMs in dedicated holes. BMMs were installed towards the free face of the blast, on ore/waste boundaries where there is a high chance of ore loss occurring.

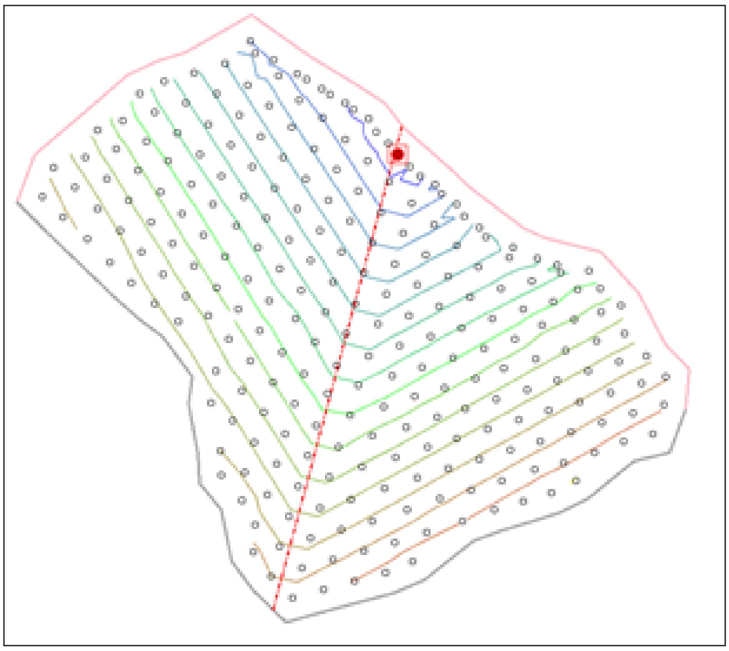

Figure 4 – Blast 220-6 Design

Table 2 – Blast Parameters

Bench Height	8m
Hole Depth	8.6m
Hole Diameter	171mm
Burden	6m

Continuation of table 2

Spacing	7m
Stemming Length	2.9m
Powder Factor	1.11kg/m3
Explosive Type	Water gel explosive
Blast Holes	253
Volume	33,109m3
Tonnage	107,546t

Results and discussion

All BMMs were recovered by onsite personnel. Post-blast detection recorded significant horizontal movement to the North-Northwest. As per the data in Table 3, BMM horizontal movement varied between 2.55m and 14.32m, and inclination varied by 92.13°. Average horizontal movement was 11.16m and the standard deviation was 4.87 m. BMMs generally moved slightly upwards as expected (creating heave) except for BMM 5 (Figure 5).

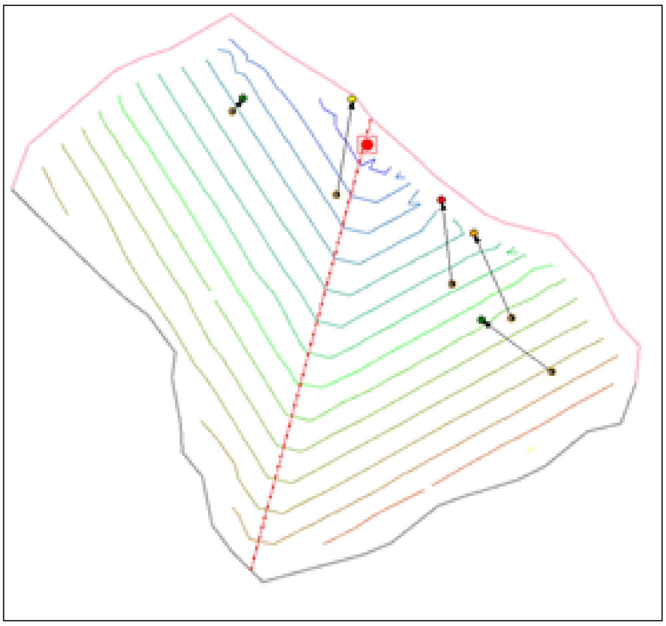

Figure 5 – Blast 220-6 BMM Vectors

Table 3 – Vector results

BMM#	Horizontal Distance (m)	Direction (°)
1	2.55	39.15
2	14.32	9.11
3	12.52	353.47
4	13.71	336.39
5	12.71	307.02

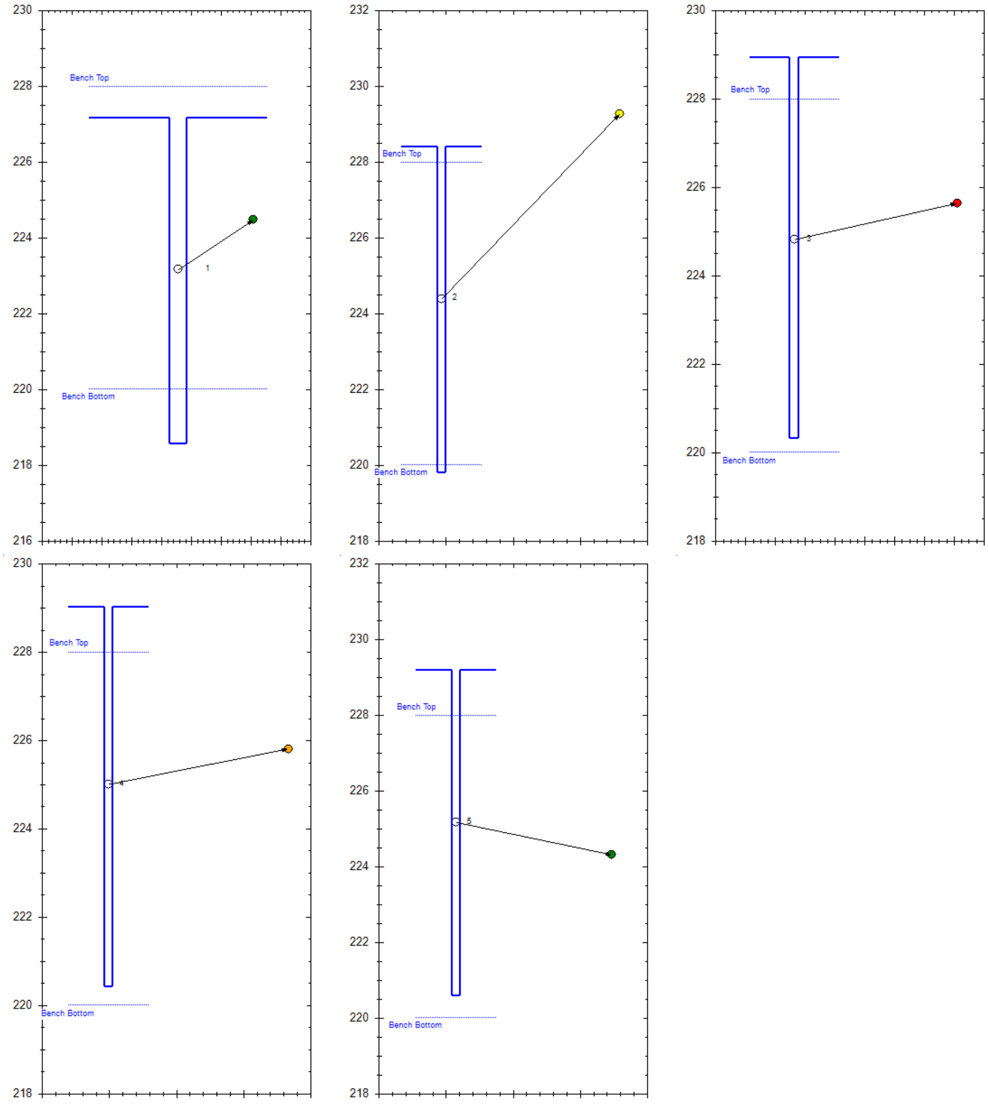

Figure 6 – Side View of BMM Vectors

The negative vertical displacement values recorded by several BMM sensors can mainly be attributed to their close proximity of the bench crest (break line). Vertical displacement data are particularly important in areas where high-grade ore zones are concentrated. Long term BMM data collected indicates that horizontal rock mass displacement is typically minimal at the bench surface, increases with depth and reaches values close to the maximum in the vicinity of the upper section of the explosive charge column, and then decreases again toward the bench toe – this is referred to as the ‘D curve’. For this reason, surface scanning alone is insufficient for accurately determining the displacement of the entire blasted rock mass.

At the same time, specialists from the Chief Geologist’s Department of Zhairem MCC emphasize that rock mass displacement within individual zones of a blast block remains highly variable and difficult to predict. The movement of blasted material strongly depends on the geo-mechanical properties of the rock mass, including lithology, structural features, and rock strength.

Economic Outcomes (Value Calculator)

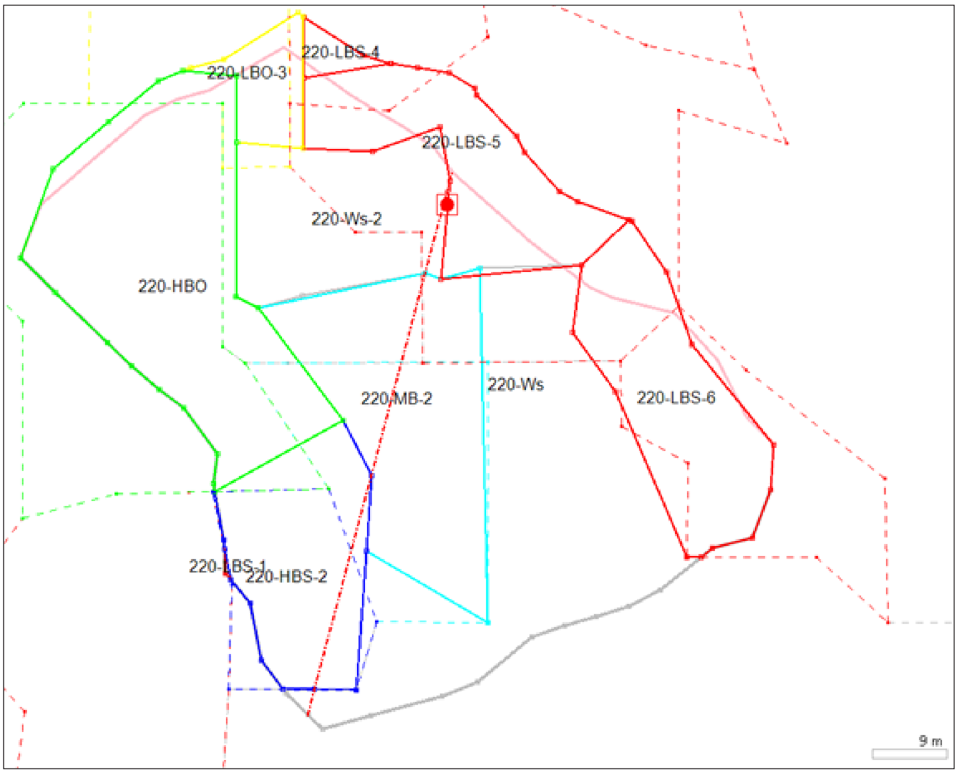

Figure 7 – Pre and Post Blast Blocks

The BMM Explorer software translates the ore blocks using the BMM vectors. Figure 7 shows the pre-blast ore-blocks (dashed lines) and translated post-blast ore-blocks (solid lines).

Table 4 – Ore Block Inputs

	Zinc			Barite			
Material	Min	Max	Average	Min	Max	Average	Density
HBO	2.19	2.19	2.19	57.13	57.13	57.13	3.29
HBS	1.96	6.16	3.57	39.15	67.12	56.12	3.36
LBO	3.63	6.41	4.95	0.00	11.07	2.10	2.46
LBS	2.28	8.02	5.45	0.00	27.11	9.27	3.27
MB	0.22	0.44	0.36	57.34	63.61	60.73	3.43
OOL	1.44	2.05	1.61	0.00	0.15	0.11	2.76
Waste	0.07	0.70	0.20	0.00	15.15	4.49	3.07

Table 5 – Economic Inputs

Ore Price – Barite	6.14 USD/tonne
Ore Price – Zinc	962.2439 USD/tonne
Mining Cost	5.6 USD/tonne
Processing Cost	10.43 USD/tonne
Processing Efficiency	75%

Table 6 – Economic Results

Ore Loss			Dilution			Misclassification	
Tonne	%	$	Tonne	%	$	T	%
6,689	8.6	68,858	8,645	11.2	138,582	8,686	11.20

The results above in Table 6 are results if blast movement had not been accounted for. These values are represented as red (ore-loss), dilution (brown) and misclassification (green) on Figure 8 below. It is noted that these values are an unreconciled potential value.

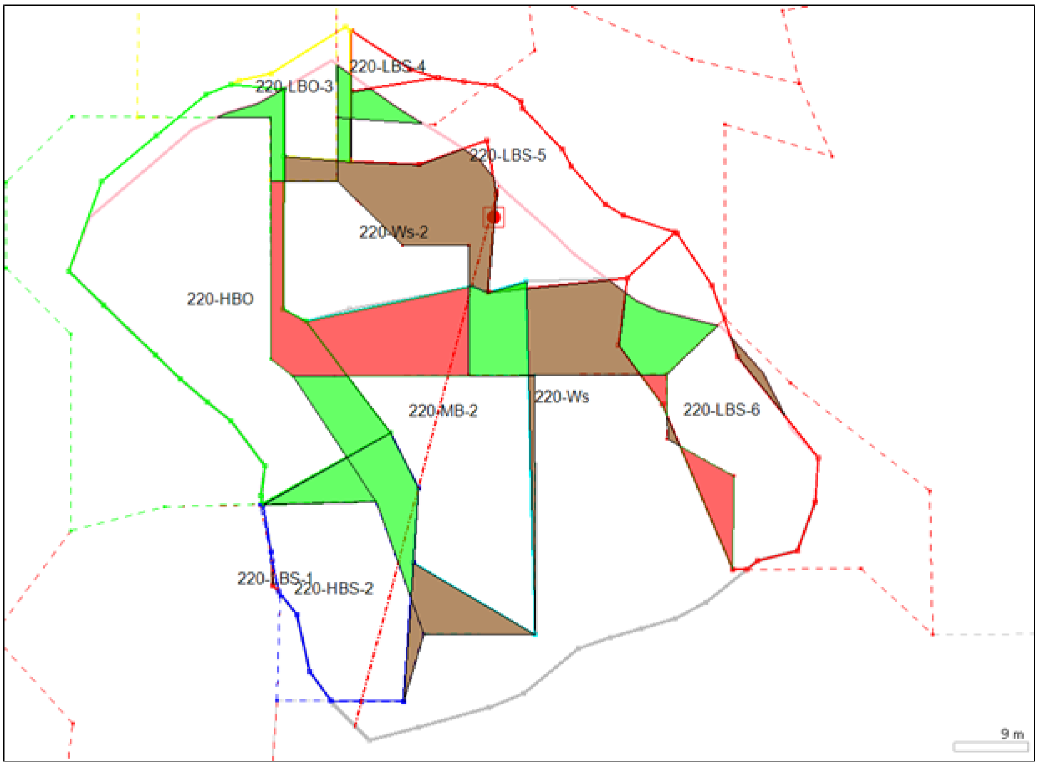

Figure 8 – Ore Loss, Dilution and Misclassification of Blast 220-6

Further Analysis

Using the BMM results, we can generate secondary results based on the movement averages and compare these to the original BMM vectors. This is akin to assumptions made in other alternative software. For this calculation we have generated vectors with an average horizontal distance of 11.16m and direction of -6.97°. In this case the discrepancy compared with the Average movement is over $55,000 in opportunity loss, highlighting the inconsistency of blasting.

Table 7 – Discrepancy between BMM System and Average Vector

	Ore Loss			Dilution			Misclassification	
	T	%	$	T	%	$	T	%
BMM System	6,689	9%	68,858	8,645	11%	138,583	8,686	11%
Average Vector	5,867	3%	46,139	10,713	10%	171,732	2,537	2%
Discrepancy	822	5%	22,719	2,068	1%	33,149	6,149	9%

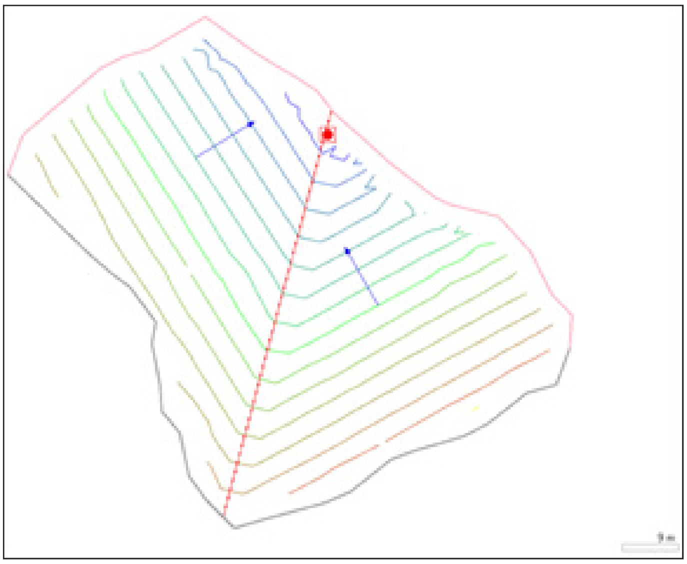

Figure 9 – Textbook Vectors

Other blasting software have traditionally relied on the assumption that ore moves perpendicular to the timing contours. This is consistent with textbook blast design. Using the software, we can replicate this assumption and compare financial results. An example of the blast direction has been displayed in Figure 9, and the horizontal distance has been entered as the average of BMM movements (11.16m). Results indicate a $60,000 discrepancy between relying on the textbook direction of movement and using real measured vectors.

Table 8 – Discrepancy between BMM system and Textbook Vector

	Ore Loss			Dilution			Misclassification	
	Tonne	%	$	Tonne	%	$	T	%
BMM System	6,689	9%	68,858	8,645	11%	138,583	8,686	11%
Textbook Vector	7,225	7%	96,827	10,643	10%	170,611	9,329	12%
Discrepancy	536	2%	27,969	1,998	1%	32,029	643	1%

Table 9 – Variability across Blast Blocks of Zhairem

No.	Bench	Blast	Min (m)	Max (m)	Block Tonnage (t)	Ore Loss (t)	Dilution (t)	Misclassification (t)
1	208	208-1-1	2.78	2.78	18,698	276	0	0
2	212	212-10 (214)	0.63	2.12	111,192	1	1,630	1,955
3	212	212-12	0.31	0.73	70,918	41	1,412	702
4	212	212-16	2.96	6.70	77,835	2,047	328	362
5	212	212-27	10.21	10.85	41,438	4,417	0	0
6	212	212-29	5.12	14.62	68,254	4,662	2,807	0
7	212	212-30	12.36	17.73	121,969	18,224	594	15,343
8	212	212-31	8.09	11.95	68,454	7,739	3,024	1,231
9	220	220-1	1.87	5.25	58,731	1,081	42	2,188

Continuation of table 9

10	220	220-18	2.64	2.64	18,631	226	115	545
11	220	220-2	1.54	4.59	90,286	659	0	4,348
12	220	220-2-1	1.54	4.59	96,058	2,995	2,271	873
13	220	220-22	1.74	4.06	121,723	131	2,308	866
14	220	220-4	3.31	13.62	69,859	791	1,334	1,676
15	220	220-5	8.33	8.33	86,782	1,012	3,675	4,562
16	220	220-6	2.55	14.32	107,546	6,689	8,645	8,686
17	224	224-3	3.47	3.47	45,671	230	1,080	0
18	224	224-6	2.36	2.60	55,599	981	0	1,343
19	224	224-8	3.05	3.05	34,403	169	9	0
20	228	228-10-1	7.84	12.88	104,693	6,155	3,529	7,395
21	228	228-15	2.99	5.43	142,884	3,725	633	6,099
22	228	228-16	5.38	6.00	65,514	989	669	3,800
23	228	228-9	3.56	6.31	47,321	4	789	5,705
24	232	232-1	2.86	2.86	69,653	447	0	0
25	232	232-4	3.62	4.68	96,724	201	1,990	2,251
26	236	236-10a	2.43	2.64	111,070	2,381	0	0
27	236	236-13s	2.55	2.55	27,093	327	0	502
28	236	236-2	8.99	12.10	83,046	3,410	1,069	3,426
29	236	236-2-1	8.99	12.10	71,000	11,080	10,971	6,401
30	236	236-8	4.63	4.63	80,729	428	2,674	0
31	240	240-1	1.50	3.63	85,204	976	365	193
32	244	244-13	2.46	7.43	34,877	2,270	818	0
33	244	244-5	3.31	3.31	77,919	431	2,026	817
34	244	244-6	4.69	8.08	82,408	1,913	0	1,802
35	248	248-1	5.79	5.79	71,388	79	830	0
36	248	248-2	1.49	2.56	64,957	578	368	448
37	308	308-13	7.44	15.97	70,268	2,225	6,163	4,631
38	308	308-22	0.78	7.07	85,679	2,918	1,444	4,763
39	316	316-16	7.23	13.12	112,426	11,237	5,193	1,820

The data presented in Table 9 indicate high spatial variability in blast-induced displacement, with no consistent relationship to bench level, block geometry, or tonnage, reflecting the complex interaction between geological conditions and blast design. Several blocks (e.g., 5, 7, 8, 29) exhibit disproportionately high ore loss relative to their tonnage, suggesting localized zones of intensified displacement or poor ore-waste boundary preservation.

Dilution values are frequently comparable to or exceed ore loss (notably in blocks 16, 20, 23, 37), which supports the conclusion that dilution represents a major economic risk, as previously identified in the economic analysis section. This reflects inefficient separation of ore and waste during blasting and highlights the sensitivity of grade control to blast-induced mixing.

Misclassification values are also significant and, in several cases (e.g., 7, 10, 12, 20), exceed both ore loss and dilution. This is particularly important in the context of polymetallic deposits such as Zhairem, where incorrect routing of material between processing streams leads to additional economic penalties beyond simple dilution effects.

Overall, Table 9 provides empirical evidence that blast-induced displacement is a dominant and highly variable driver of ore loss, dilution, and misclassification, further justifying the need for direct measurement approaches such as BMM for effective grade control.

The results from Blast 220-6 at the Zhairem Mining and Concentrating Complex clearly demonstrate that blast-induced movement is both significant in magnitude and highly spatially variable, with direct consequences for grade control performance and economic outcomes. Measured displacement ranges (2.55–14.32 m) and directional variability exceeding 90° demonstrate that blast movement cannot be reliably represented using a single average vector or deterministic approach.

At Zhairem, as in many contemporary open-pit operations, excavation accuracy of ±0.2 m is achievable due to high-precision guidance systems on loading equipment. However, the results show that pre-blast ore polygons can be displaced by more than an order of magnitude greater than excavation tolerances. Without correction, this discrepancy leads directly to systematic ore loss, dilution, and misclassification, regardless of how accurately the dig design is followed. In this sense, blast movement represents a dominant source of grade control error, overriding downstream improvements in equipment accuracy if left unaccounted for.

Mining based on in-situ polygons without accounting for blast movement would result in approximately 6,689 t of ore lost and 8,645 t of dilution, with a combined economic impact exceeding USD 200,000 for a single blast. This highlights the strong economic sensitivity of grade control to spatial uncertainty at ore boundaries.

The BMM system is typically supplied as part of an integrated solution; however, for the purposes of this analysis, a simplified cost assumption is adopted. It is assumed that drilling and labour costs amount to approximately USD 500 per BMM unit installed. Under this assumption, the total cost associated with deploying five BMMs to track blast-induced movement would be approximately USD 2,500. On this basis, the resulting return on investment (ROI) can be evaluated by comparing this implementation cost against the quantified value preserved through reductions in ore loss, dilution, and misclassification.

Dilution represents a major economic penalty due to additional mining and processing costs, while misclassification further increases losses by directing material to inappropriate processing streams.

A key methodological insight from this study is the demonstrated inadequacy of using a limited number of BMMs to represent entire ore-waste contacts. Although only five BMMs were installed in Blast 220-6, the observed variability suggests that even this number may be insufficient for complex geological settings with multiple ore types and irregular boundaries. This finding supports the argument that BMM deployment strategies must be tailored to geological complexity and economic risk, rather than applied as a uniform, minimum-cost solution. Increasing sensor density at high-value or high-risk contacts is likely to yield disproportionate economic returns.

While the results from Zhairem demonstrate clear benefits, several limitations should be acknowledged. While detailed economic evaluation is demonstrated using Blast 220-6, the analysis is supported by a dataset of 20 blasts from the Zhairem operation, enabling assessment of variability in ore loss, dilution, and misclassification across different conditions. A simplified sensitivity analysis indicates that the economic impact remains significant under a wide range of input assumptions. For example, a ±20% variation in metal prices or processing recovery results in proportional changes in calculated value; however, the relative magnitude of losses due to blast movement remains consistently high. Future work should focus on multi-blast datasets to assess variability over time, optimise BMM placement strategies, and further integrate blast movement data with comminution and plant performance models.

Correlation analysis

A correlation analysis was performed to evaluate the relationship between blast-induced displacement and grade control performance indicators. Displacement values were approximated using the midpoint of the reported range for each blast. The results indicate a moderate to strong positive correlation between displacement and ore loss, suggesting that increased blast movement leads to higher loss of valuable material. Similar relationships were observed for dilution and misclassification, although with slightly lower correlation strength.

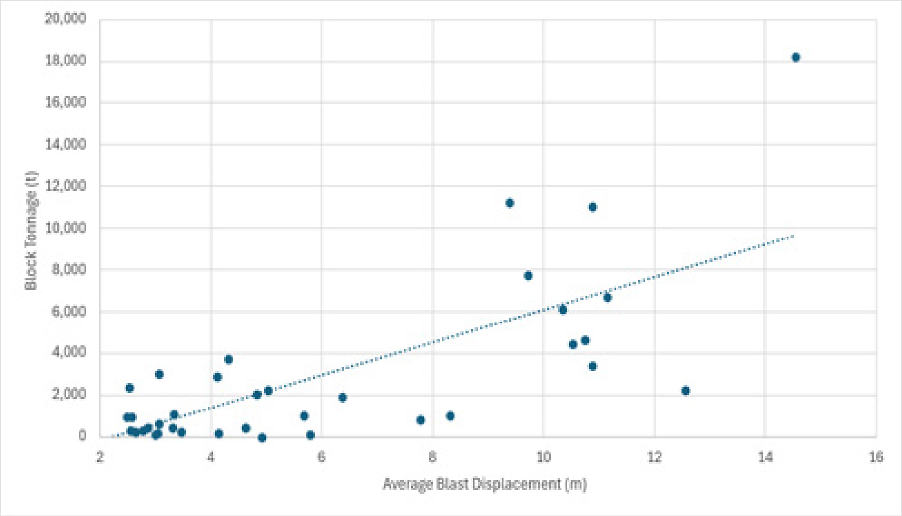

Figure 10 – Correlation between Displacement and Ore Loss

The relationship between blast-induced displacement and ore loss is illustrated in Figure 10 (R2 = 0.553). A positive trend can be observed, indicating that larger displacement distances generally correspond to increased ore loss. Although some scatter is present due to geological variability, the overall pattern confirms that displacement is a key driver of ore loss in open-pit operations.

Conclusions

This study demonstrates that blast-induced rock movement represents a critical and quantifiable source of error in grade control for open-pit mining. The results show that displacement is highly variable and cannot be reliably approximated using deterministic or averaged approaches.

The integration of BMM data into grade control workflows enables the correction of ore boundaries prior to excavation, significantly reducing ore loss, dilution, and misclassification. The economic analysis confirms that even a single blast can generate value losses exceeding USD 200,000 when movement is not accounted for.

From a methodological perspective, the study highlights the limitations of predictive modelling and supports the use of direct measurement techniques in complex geological environments. The findings also indicate that the effectiveness of BMM depends on appropriate sensor placement and should be aligned with geological variability and economic risk.

Although a detailed analysis is presented for Blast 220-6, the study is supported by a broader dataset of multiple blasts from the Zhairem minesite, enabling validation of observed trends across varying conditions. This integration of detailed case analysis with multi-blast variability enhances the robustness of the results and supports the wider applicability of the proposed methodology for linking blast-induced displacement with economic performance.

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ЖАЙРЕМ КЕНОРНЫНДА ЖАРЫЛЫС ЖҰМЫСТАРЫ КЕЗІНДЕ КЕННІҢ ЖОҒАЛЫМДАРЫ МЕН ҚҰНАРСЫЗДАНУЫН ЕСКЕРЕ ОТЫРЫП, ТАУЖЫНЫСТАРДЫҢ ЖЫЛЖУЫ ЖӘНЕ КЕН САПАСЫН БАҚЫЛАУ

Аңдатпа

Мақала карьерлерде кен сапасын бақылау тұрғысынан жарылыс жұмыстары кезінде таужыныстардың жылжуын бақылаудың (BMM) экономикалық тиімділігін талқылайды. Жарылыс жұмыстары кезінде таужыныстардың жылжуы карьерлерде кен сапасын тиімді бақылауға кедергі келтіретін негізгі факторлардың бірі. Жарылыс кезіндегі есепке алынбаған ығысулар жиі кеннің құнарсыздануына, алынатын кеннің жоғалуына және қате классификацияға әкеліп соғып, нәтижесінде өңдеу мен экономикалық тиімділікті төмендетеді. Зерттеу жарылыс нәтижесінде пайда болатын таужыныс жылжуының табиғаты стохастикалық екендігіне және оны тек детерминистік модельдеу арқылы сенімді түрде қайта жаңғырту мүмкін еместігіне негізделген. Сондықтан жоғары дәлдіктегі сапаны бақылау үшін кен орнында тікелей өлшеулер жүргізу қажет. Жарылыс блогындағы бірнеше бақылау нүктесінен үшөлшемді ығысу векторларын тіркеу арқылы BMM жүйесі жарылыстан кейін кен шекараларын дәлірек қалпына келтіруге мүмкіндік береді. Бұл көпнүктелі тәсіл кеңістіктік өзгергіштікті ескереді және қазу жұмыстарына дейінгі құрам жоспарларын түзету үшін сенімді негіз ұсынады. 2024 ж. Жайрем кен байыту комбинатында BMM жүйесінің пилоттық енгізілуі жүзеге асырылды, ал қазіргі уақытта бұл жүйе Қазақстандағы бірнеше тау-кен компаниясында қолданылуда. Жайрем кен орнынан алынған деректерді пайдалана отырып, зерттеу бақылаусыз таужыныс ығысуының операциялық салдарын, соның ішінде кеннің жоғалуын, құнарсыздануын және қате классификацияны сандық түрде бағалайды. Нәтижелер бос жыныстар мен кен арасындағы шекараларды дәлірек анықтау ресурс тиімділігін арттырып, пайдалылықтың тікелей өсуіне ықпал ететінін көрсетеді. Осы нәтижелер негізінде мақалада жарылысты бақылау жүйелеріне инвестициялық шешімдерді қолдауға арналған қаржылық шығындарды бағалау құралы ұсынылады. Бұл құрал операторларға BMM енгізудің шығын-пайда арақатынасын жүйелі түрде бағалауға және сапаны бақылау стратегияларын кең экономикалық шеңберде оңтайландыруға мүмкіндік береді.

Түйін сөздер: жарылыс кезінде кеннің ығысуын бақылау, кеннің сапасын бақылау, кен жоғалымдары, кенді құнарсыздандыру, қате классификация, инвестициялардың өтелімділігі, Жайрем, Казцинк, Glencore, кен, карьер, цинк, барит, минерализация түрі, экскавация.

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МОНИТОРИНГ СМЕЩЕНИЯ ГОРНЫХ ПОРОД ВО ВРЕМЯ ВЗРЫВНЫХ РАБОТ ПРИ КОНТРОЛЕ КАЧЕСТВА РУДЫ НА МЕСТОРОЖДЕНИИ ЖАЙРЕМ С УЧЕТОМ ПОТЕРЬ И РАЗУБОЖИВАНИЯ РУДЫ

Аннотация

В данной статье рассматривается экономическая эффективность мониторинга сдвигов породы при взрывах (BMM) с учетом контроля качества руды в карьерах. Перемещения горной массы при взрывах остаются одним из основных факторов, ограничивающих эффективный контроль качества руды в карьерах. Неучтенные смещения при взрывах часто приводят к разубоживанию руды, потере полезного ископаемого и неправильной классификации, что в итоге снижает эффективность переработки и экономическую рентабельность. Исследование основано на предпосылке, что смещение горных пород, вызванное взрывом, по своей природе является стохастическим и не может быть надежно воспроизведено с помощью одного только детерминированного моделирования; поэтому для высокоточного контроля качества требуются прямые измерения на месторождении. За счет фиксации трехмерных векторов смещения из нескольких точек мониторинга в пределах взрывного блока BMM позволяет более точно восстанавливать границы руды после взрыва. Этот многоточечный подход учитывает пространственную изменчивость и обеспечивает надежную основу для корректировки сортовых планов перед началом экскавации. В 2024 г. пилотная реализация системы BMM была начата на Жайремском горно-обогатительном комбинате (ГОК), и система применяется в нескольких горнодобывающих компаниях Казахстана. Используя полевые данные с Жайремского месторождения, в исследовании количественно оцениваются эксплуатационные последствия неконтролируемого сдвига породы, включая потери руды, разубоживание и неправильную классификацию. Результаты показывают, что улучшенное определение границ между пустой породой и рудой повышает эффективность использования ресурсов и напрямую способствует увеличению прибыльности. На основе этих выводов в статье предлагается инструмент оценки финансовой стоимости, предназначенный для поддержки инвестиционных решений, связанных с системами мониторинга движения взрыва, что позволяет операторам систематически оценивать соотношение затрат и выгод внедрения BMM и оптимизировать стратегии контроля качества в более широких экономических рамках.

Ключевые слова: мониторинг сдвига пород при взрыве, контроль за качеством руды, потеря руды, разубоживание, ошибочная классификация, окупаемость инвестиций, Жайрем, Казцинк, Glencore, руда, карьер, цинк, барит, тип минерализации, экскавация.