

Numerical assessment of explosive charge misfire impact on gravity flow in sublevel caving

V. Lapčević^a, A. Khodayari^b, C. Xu^b, S. Torbica^c and P. Dowd^b

^aUniversity of Belgrade – Faculty of Mining and Geology, Đušina 7, Belgrade, Serbia

^bSchool of Chemical Engineering, University of Adelaide, South Australia, SA 5005, Australia

^cOwl and Fox – Mining Consultants, Cara Dušana 67/3, Belgrade, Serbia

ABSTRACT

Blasting is a major factor influencing the success of sublevel caving operations and is the only controllable element in this process. The fragmentation of blasted material, which is unevenly distributed in space, impacts both the dilution and recovery rates. Explosive charge misfire results in unbroken rock within the blasting pattern, which negatively impacts both safety and the efficiency of operations. A misfire results in coarser fragmentation around the charge, further disrupting the gravity flow and increasing dilution.

The impact of explosive charge misfire on the spatial size distribution of fragments and the subsequent effect on gravity flow in sublevel caving is analyzed using a 3D blast fragmentation model. The 3D spatial size distribution of fragments is determined for various scenarios. Results are then utilized to create a Discrete Element Method (DEM) model, which is used to simulate the gravity flow for each scenario. In the DEM simulations, ore dilution is monitored and compared with a base scenario that assumes no misfires. Results show a clear increase of ore dilution in misfire scenarios.

1 INTRODUCTION

Sublevel caving is an underground mining method in which ore is extracted by blasting it from sublevel drifts using ring blasting patterns. During the loading process, the blasted ore and caved waste material are moved by gravity. As the loading process continues, the inflow of waste rock material increases until the ore grade becomes economically insignificant.

Over time, sublevel caving has evolved, characterized by a significant increase in sublevel heights. This increase in sublevel heights has led to higher draw heights, which in turn demands higher quality in drilling and blasting processes. Blasting is one of the most influential factors in sublevel caving and is the only factor that can be controlled. Poor blasting practices can result in operational difficulties and increased ore dilution. The impact of blasting on sublevel caving has been a major topic of research for many researchers,

highlighting its critical role (Brunton et al., 2010, Campbell, 2018, Zhang & Wimmer, 2018). Additionally, the properties of waste material also affect the gravity flow, further emphasizing the complexity of optimizing sublevel caving operations (Lapčević & Torbica, 2017).

Blast fragmentation is considered a major factor influencing the formation of gravity flow in Sublevel Caving (SLC). Since SLC employs ring or fan blasting patterns, the spatial size distribution of the blasted fragments is uneven. In areas where explosive charges are positioned closer together, finer fragmentation occurs, and conversely, areas with charges spaced further apart experience coarser fragmentation. Finer fragments encounter lower kinematic resistance during movement and thus move faster towards the draw point. In contrast, coarser fragments face increased kinematic resistance and move slower. It is not uncommon for coarse fragments

to cause hang-ups, disrupting the flow. The ultimate goal in SLC is to achieve as uniform a spatial size distribution as possible, without oversized rock blocks that could result in hang-ups.

It has been well observed that the central axis of the gravity flow exhibits the highest velocity of fragment movement, with velocity decreasing towards the sides of the stope. This phenomenon has been documented and analyzed in depth, as highlighted by Kvapil's research (Kvapil, 1992).

Understanding that the spatial size distribution of blasted ore fragments has a dominant effect on dilution and recovery in SLC leads to the conclusion that any disturbance in the blasting process will result in a disturbance of the gravity flow. Operational malfunctions related to the initiation of explosive charges, known as misfires, are known to occur. If a certain explosive charge within the blasting pattern is not activated, part of the rock mass will remain unfragmented, resulting in undesirably coarser fragmentation around that charge. Besides creating a safety risk, the resulting fragmentation has significant implications for production efficiency.

Evaluating blast fragmentation has been a key topic in mining engineering, with many available models providing reliable results primarily for bench blasting, where boreholes are drilled in parallel. However, evaluating blast fragmentation for ring blasting scenarios has posed a significant challenge. Most available models tend to evaluate only the size distribution, omitting the spatial size distribution, which could be crucial for understanding the behavior of rock material under the draw (Lith et al, 2004, Yi et al., 2017, Manzoor et al., 2022, Yi et al., 2022). This gap highlights the need for more comprehensive models that consider both the size and spatial distribution of fragments to better predict and manage the outcomes of ring blasting in mining operations.

This research focuses on the application of a 3D blast fragmentation model, integrating it with the discrete element method, to assess how the spatial size distribution of blasted ore fragments

in SLC influences the dilution and recovery of the ore. Particular attention is given to the impact of explosive charge misfires, as these directly result in an undesired spatial size distribution of rock fragments. By examining these aspects, the study aims to provide insights into optimizing blasting processes and improving the overall efficiency and effectiveness of ore extraction in SLC operations.

2 METHODOLOGY

A misfire of explosive charges can result in an unbroken part of the rock mass or significantly coarser fragmentation in the affected area. Consequently, there is a need to manage boulders, which carries an additional risk of encountering undetonated explosives. In open-pit blasts or open stoping underground mines, handling these boulders is feasible because access to the oversized rock blocks is possible. However, in sublevel caving operations, these rock blocks are located within the gravity flow, significantly impacting the flow. The impact of misfires on gravity flow in sublevel caving is analyzed using a 3D blast fragmentation model and the discrete element method (DEM). A fragmentation model, capable of simulating ring blasts and assessing the spatial size distribution, is employed to create various scenarios considering misfire of different charges within the pattern. This model provides the input size distribution of blasted ore fragments for the DEM simulations. As a result dilution of the ore is observed and compared to the base case scenario.

2.1 3D evaluation of blast fragmentation

The evaluation of blast-induced fragmentation is conducted using a 3D blast fragmentation model (Lapčević et al., 2023), which is validated with in-situ data specifically for ring blasts. This model has a universal applicability, meaning it can simulate bench, ring, and tunneling blasts in terms of blasting patterns. Furthermore, it can directly model both borehole deviation and explosive charge misfires. To provide input for the discrete element method models, various scenarios are considered. The base case scenario assumes that no misfires occur, and all explosive

charges detonate as planned (**Error! Reference source not found.**). In contrast, other scenarios account for potential misfires of certain explosive charges, leading to coarser fragmentation in the affected areas.

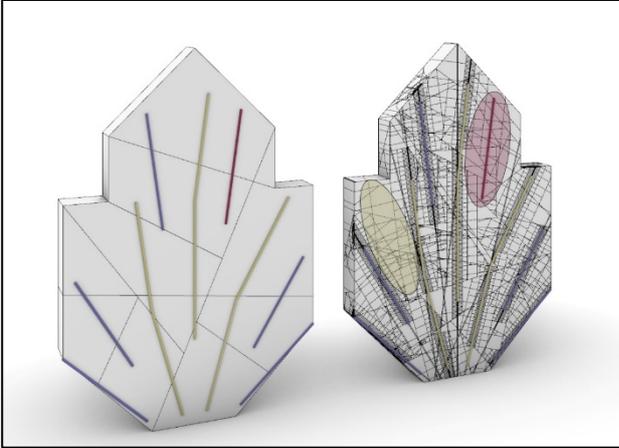


Figure 1 Borehole deviation and misfire handling in the 3D fragmentation model (Lapčević et al., 2023).

A total of five misfire scenarios were generated to evaluate the influence of a single charge misfire. Specifically, the first misfire scenario assumes that the central charge failed to detonate, with each subsequent scenario considering a single charge misfire moving towards the outermost charges.

In the second stage of the analysis, 20 scenarios were examined, each involving misfires of two explosive charges. These scenarios represent 20 possible combinations of misfired charges.

Considering **Error! Reference source not found.** simulated scenarios are given in Table 1.

Table 1 Misfire scenarios

1 charge misfire	2 charge misfire	
1	1 + 2R	3L + 4R
2R	1 + 3R	3L + 5R
3R	1 + 4R	4L + 2R
4R	1 + 5R	4L + 3R
5R	2L + 2R	4L + 4R
	2L + 3R	4L + 5R
	2L + 4R	5L + 2R
	2L + 5R	5L + 3R
	3L + 2R	5L + 4R
	3L + 3R	5L + 5R

The properties of the explosives and the rock are detailed in the provided Table 2.

Table 2 Rock and explosive properties

Tensile strength	7MPa
Poisson ratio	0.25
VOD	4 km/s
Explosive density	1.15 g/cm ³
Hole diameter	89mm
Charge diameter	89mm
Burden	2.3m

Blasting pattern with charge initiation sequence is illustrated in **Error! Reference source not found.** Since 3D blast fragmentation model relies on fragmentation of the primary blocks intersected by explosive charges, arbitrary fracture network is used. Rock jointing influence is not investigated within this research.

Fragmentation results for different misfire positions are given in Figure 3. And as can be seen each scenario involving the misfire results in coarser fragmentation.

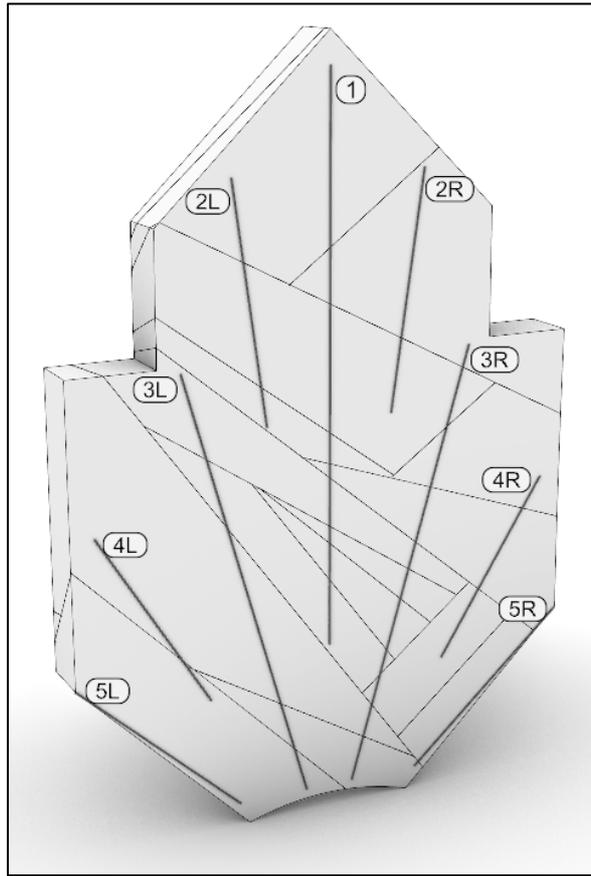


Figure 2 Blasting pattern with firing sequence.

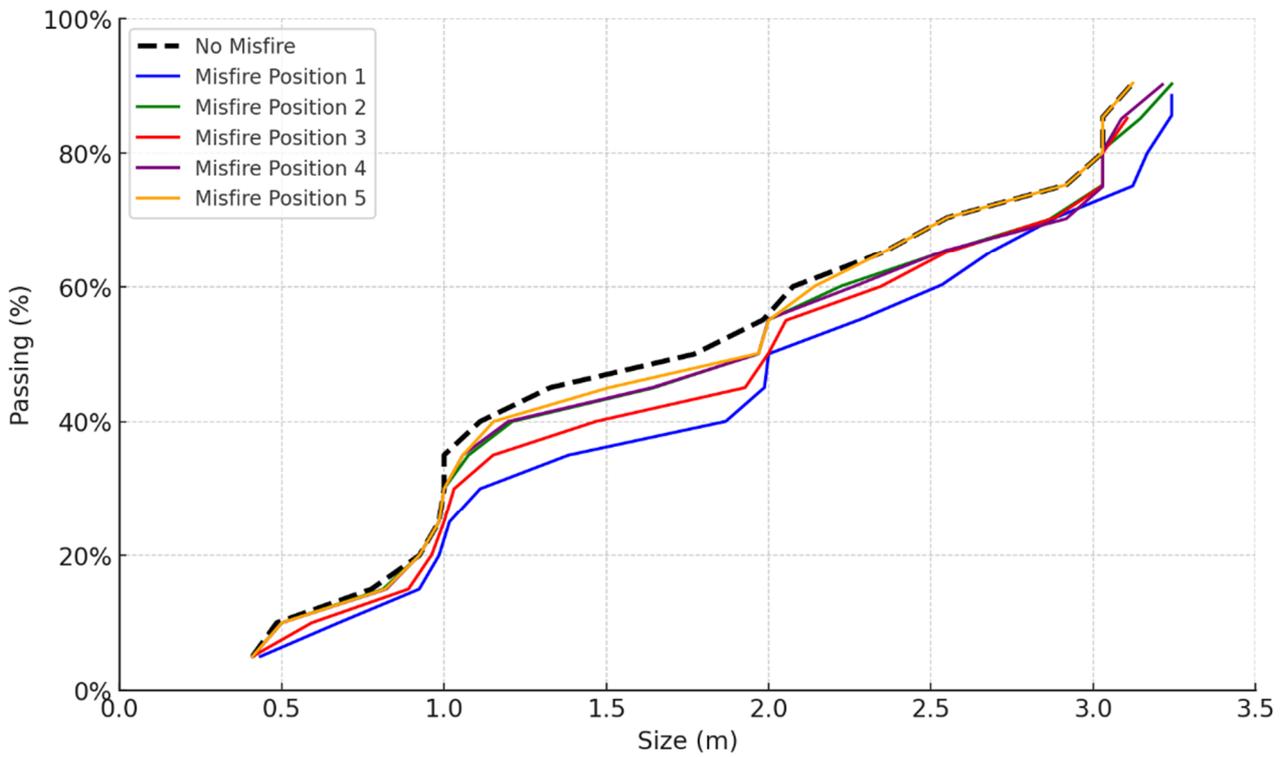


Figure 3 Fragment size distribution for different scenarios.

2.2 DEM models

SLC gravity flow is modeled using discrete element method and YADE code. This methodology has been proven as reliable for modeling different processes that involve granular materials (Kozicki & Donze, 2009). Model geometry resembles typical sublevel caving layout (DeGagne, 2005). Key aspect of the models is the spatial size distribution of the ore fragments that is inherited from the 3D blast fragmentation model. For this purpose fragmentation code that operates under the Rhino3D (McNeel et al., 2010) is adjusted to provide input for the DEM models. This primarily relates to the exporting of the fragmentation results in suitable manner, meaning that each fragment centroid coordinates are exported along with the corresponding size of the fragment. Since fragments generated within Rhino3D using fragmentation model have complex polyhedral shape, particle radii are calculated from fragment volume. In other words, sphere of equivalent volume as fragment is used to determine the radius of spherical element in DEM model. Waste material distribution is arbitrary and constant in all simulations. Material properties in DEM models is given in Table 3. DEM model setup is illustrated in Figure 4.

Table 3 Material properties in DEM models

Material	Elastic modulus (Pa)	Friction angle (°)	Density (t/m ³)
Ore	10 ⁸	35	3.2
Waste	10 ⁸	35	2.7
External	10 ¹⁰	35	2.7

Each model is process until 120% extraction is achieved and during the simulation ore recovery and dilution are calculated using following expressions:

$$R_o = \frac{m_r}{M_r} \cdot 100\% \tag{1}$$

Where:

- R_o – ore recovery (%)
- m_r – loaded ore mass (t)
- M_r – total mass of blasted ore (t)

$$D = \frac{m_w}{m_w + m_r} \tag{2}$$

Where:

- D – ore dilution (%)
- m_w – loaded waste mass (t)

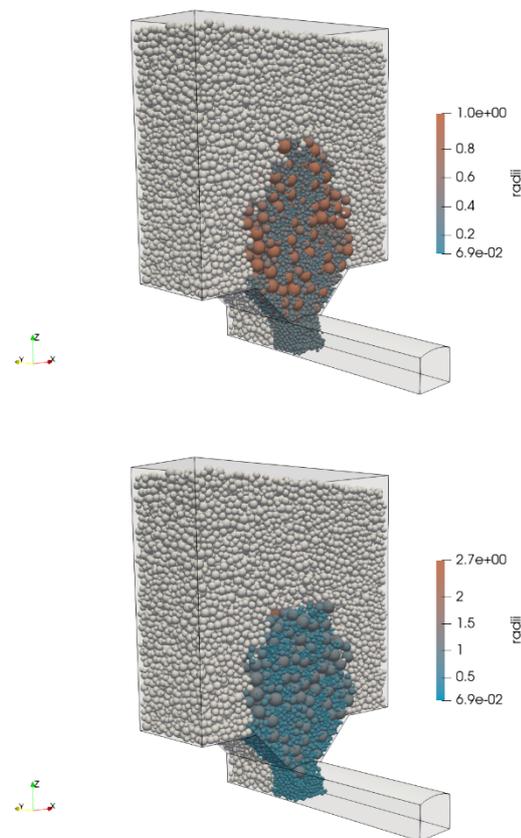


Figure 4 Dem models for base case and central charge misfire.

3 RESULTS

A total of 25 Discrete Element Method (DEM) simulations were conducted using the YADE code, encompassing a variety of scenarios to assess the impact of misfires on ore dilution in SLC. These simulations included 5 cases featuring a single charge misfire and 20 cases involving double charge misfires at different positions. All DEM models were identical in

terms of setup, with the only variable being the distribution of blasted ore across the different scenarios. Each model was then compared to a base case scenario that involved no misfires, allowing for a comprehensive analysis of how misfires—and their locations—affect the overall efficiency and effectiveness of the SLC process. This approach provided a detailed understanding of the potential variations in ore dilution resulting from different misfire scenarios, contributing valuable insights into the optimization of blasting operations in SLC.

Figure 5 illustrates the outcomes for scenarios involving a single charge misfire within the given blasting pattern. The data clearly show that a misfire of an explosive charge at any position results in increased ore dilution. Notably, charges located centrally and those adjacent to the major vertical axis of the gravity flow exhibit the highest rates of dilution. This finding not only confirms the significant impact of misfires on the outcomes of SLC operations but also strongly suggests that the spatial size distribution of the blasted ore fragments is a dominant factor in determining these outcomes.

The implications of these results extend beyond the identification of problem areas within the blasting process. They point towards the potential for controlling gravity flow through the strategic manipulation of spatial fragment size distribution. By understanding and applying principles that govern the movement of blasted materials, it may be possible to achieve better control over ore dilution during operations. This approach opens up new ground for research and practical application, suggesting that advancements in the management of spatial fragment size distribution could lead to significant improvements in the efficiency and effectiveness of SLC.

The scenarios involving double charge misfires, as presented in Figure 6 through Figure 10, underscore the significant impact of undesired fragment size distribution across the space. As anticipated, the majority of these cases demonstrate an increase in dilution greater than that observed in scenarios with a single charge misfire. However, the outcomes did not always

align with logical expectations. Specifically, a closer examination of Figure 6 reveals that one particular combination of misfired charges resulted in a slightly decreased dilution compared to the base case scenario. Notably, the DEM model did not exhibit any errors that could account for this unexpected result.

The main conclusion to be drawn from these findings is that specific spatial distributions of blasted ore fragments can lead to outcomes that differ from expected patterns. This suggests that the relationship between spatial distribution and ore dilution in SLC is complex and may not always be intuitive. Consequently, it indicates the need for further research to provide conclusive evidence supporting such SLC behavior.

Scenarios 2, 3, and 5 did not present any outcomes that deviated significantly from the expected results for the simulated cases of double charge misfires. These scenarios behaved in a manner consistent with the theoretical understanding of how multiple misfires should impact ore dilution and material flow within the stope. However, scenario 4 stood out by resulting in the highest dilution rates compared to all other scenarios, including the unexpected outcomes observed in scenario 1.

Notably, in scenario 4, as with scenario 1, no errors were detected in DEM simulations that could explain the elevated dilution rates. No hang-ups were observed that might have otherwise obstructed the flow of ore particles, thereby inadvertently increasing the inflow of waste material to the draw point. This indicates that the increased dilution observed in scenario 4 was a direct result of the spatial distribution and movement dynamics of the fragmented rock, rather than a simulation error or a physical blockage within the model.

The outcomes of scenario 4 emphasize the complexity of predicting the impact of blast design and execution on ore dilution and recovery in SLC operations. They underscore the need for a deeper understanding of the interplay between blast-induced fragmentation, spatial distribution of blasted material, and the subsequent material flow dynamics. This

scenario highlights the critical importance of planning and executing blasts in SLC, to considering a wide range of factors when minimize dilution and maximize ore recovery.

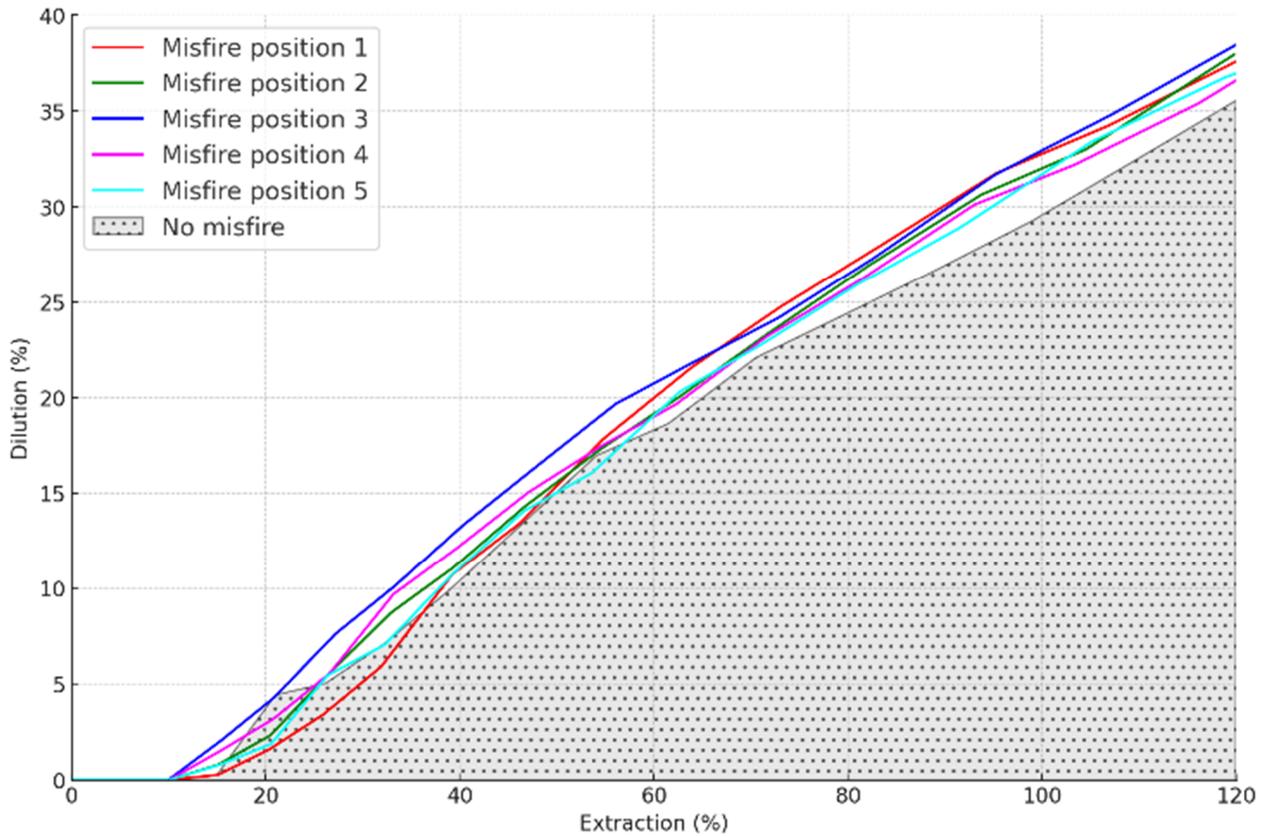


Figure 5 Ore dilution results for single charge misfire scenario.

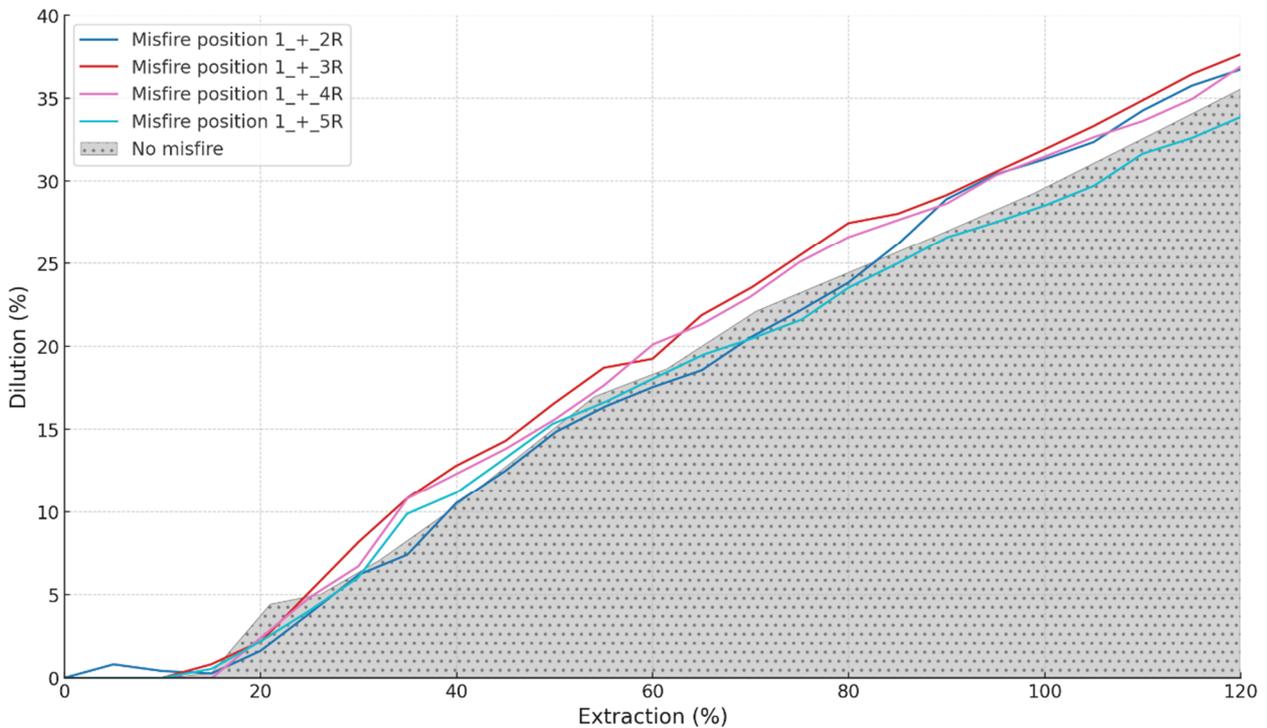


Figure 6 Ore dilution results for double charge misfire – scenarios 1.

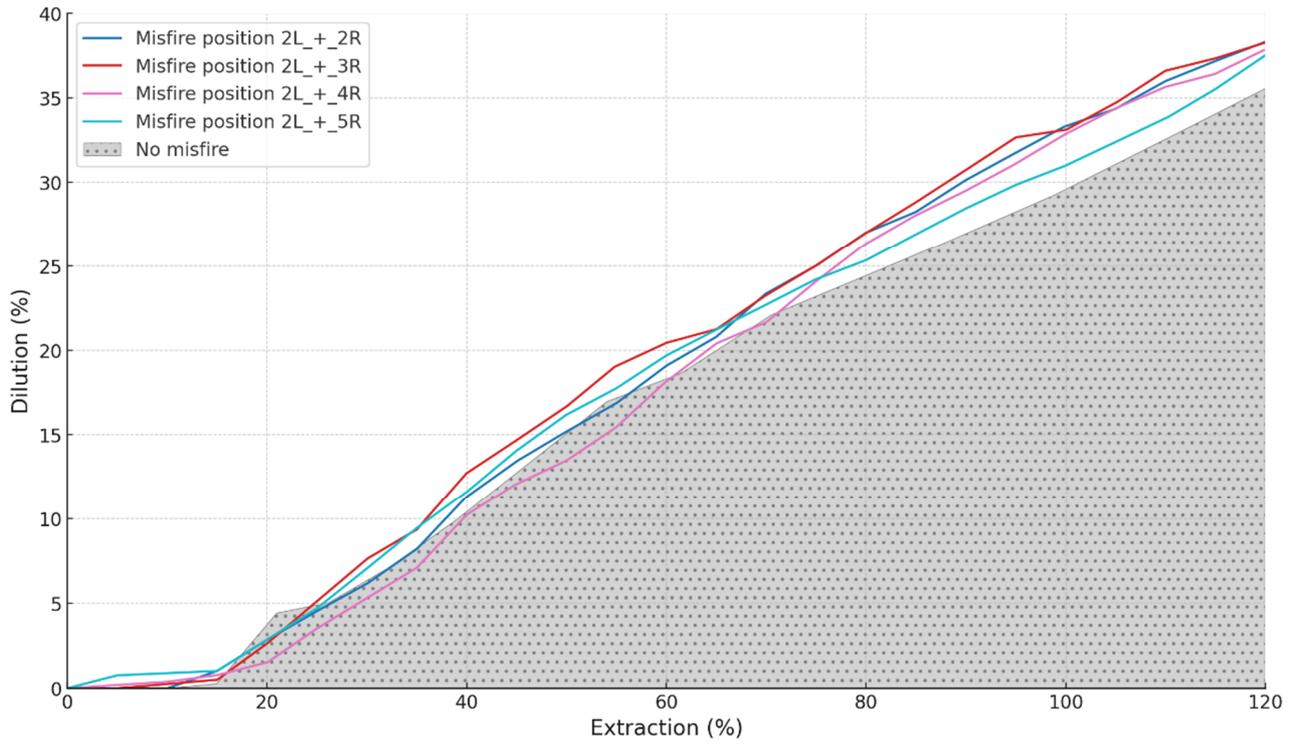


Figure 7 Ore dilution results for double charge misfire – scenario 2.

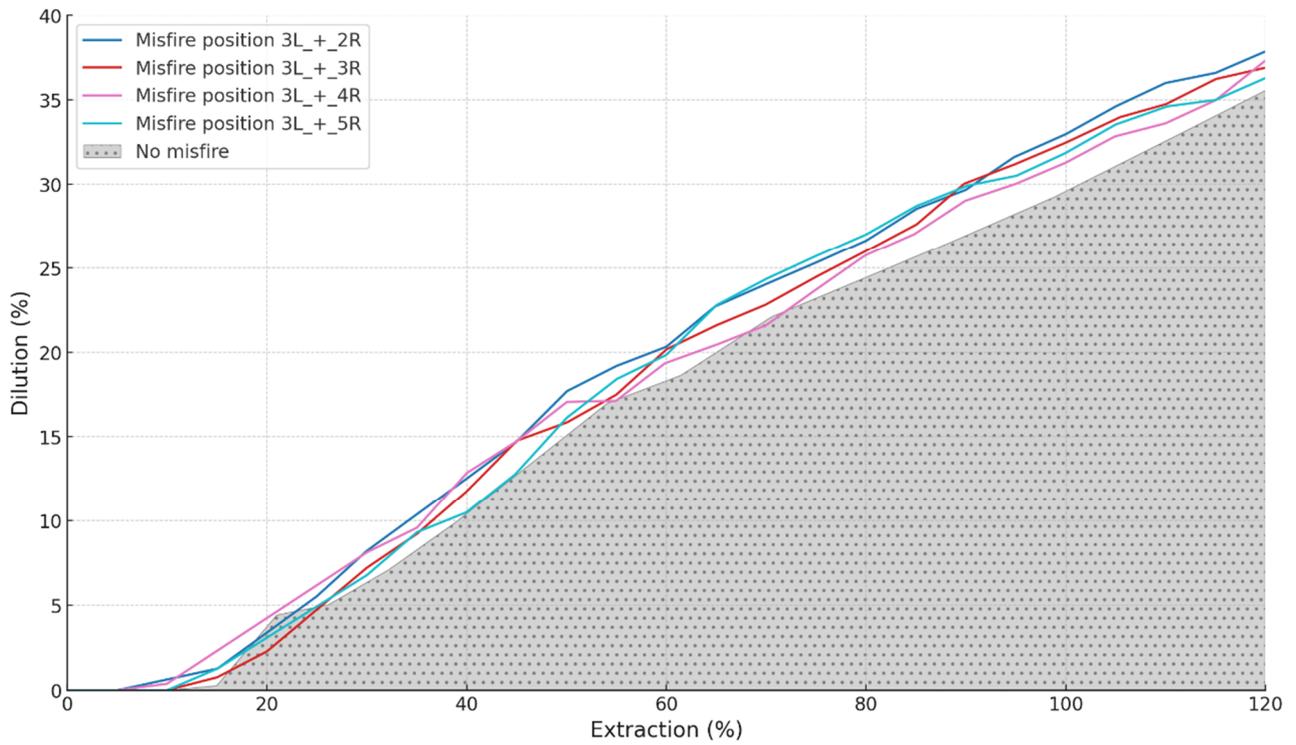


Figure 8 Ore dilution results for double charge misfire – scenario 3.

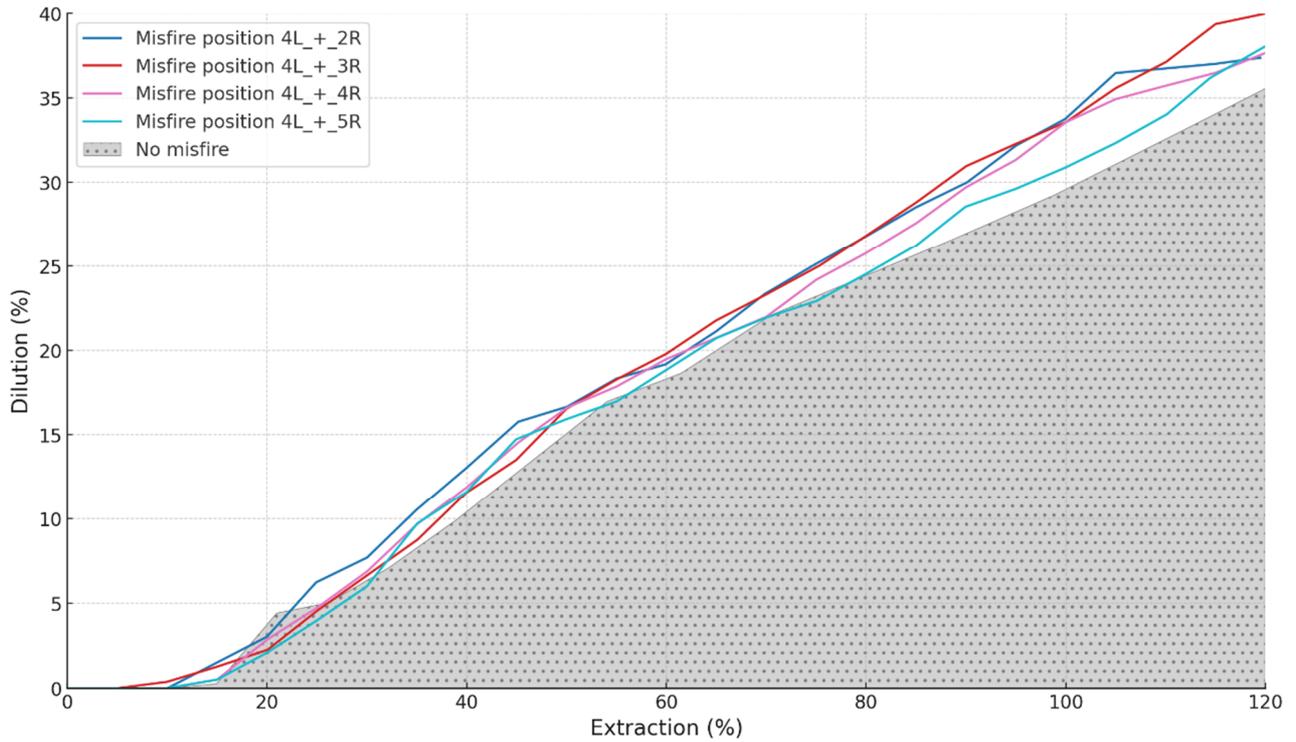


Figure 9 Ore dilution results for double charge misfire – scenario 4.

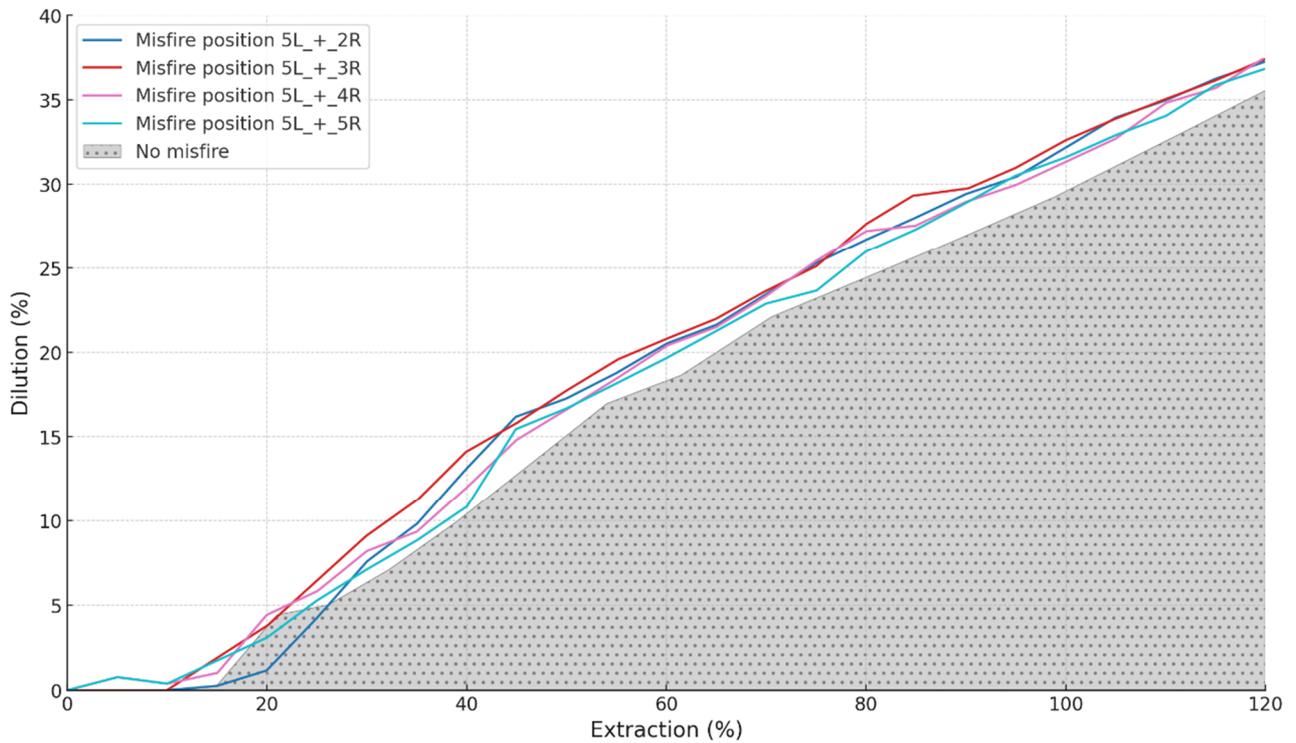


Figure 10 Ore dilution results for double charge misfire – scenarios 5.

4 CONCLUSION

In this study, a 3D blast fragmentation model was utilized to analyze a series of scenarios in

which different positions of misfires were compared to a base case scenario without misfires. The fragmentation analysis clearly indicated that each scenario involving a misfire

resulted in a coarser fragment size distribution compared to the base case. The most distinct differences were observed between the base case and the scenario simulating a misfire of the central explosive charge, with this distinction becoming less pronounced in other cases. Subsequent analysis of ore dilution revealed that, when comparing X50 values the differences were not significantly marked to draw strong conclusions about how the mean fragment size may influence SLC dilution. In some scenarios, certain curves overlapped, further implying that the spatial size distribution is a key parameter to consider. This indicates that while mean fragment size does have an impact, the spatial distribution of fragments plays a crucial role in affecting the dilution in Sublevel Caving operations.

Discrete Element Method simulations have corroborated the trend observed in the 3D blast fragmentation analysis, but with clearer implications. The simulations suggest that a misfire in the explosive charge located in the central hole position has a major impact on ore dilution when single misfire occurs. The influence of misfires decreases progressively from the central position towards the lateral ones. In scenarios involving a double charge misfire, the influence on ore dilution is further emphasized, with an increase in dilution observed. While the central position is identified as the most sensitive to disturbances in gravity flow, there are instances where coarse fragmentation in other parts of the gravity flow can significantly impact ore dilution. This is notably illustrated in scenario 4, where coarse fragmentation outside the central area still leads to a notable increase in ore dilution.

This finding confirms the significance of how explosive charge misfires affect gravity flow in SLC, further emphasizing that spatial size distribution is a key factor in ore dilution. Consequently, conducting high-quality blasting operations is crucial for maintaining optimal production results. Avoiding explosive misfires assume accurate drilling, high quality explosive usage and proper design of the blasting pattern, as well as proper storage of explosives and

detonators, skilled and trained personnel, following the standards and protocols.

Blasting has long been recognized as the dominant and only controllable process in SLC, yet the tools and depth of understanding surrounding the blasting processes continue to evolve. The results and methodologies presented in this research open new approaches for complex and comprehensive simulations of SLC.

REFERENCES

- Brunton, I. D., Fraser, S. J., Hodgkinson, J. H. & Stewart, P. C. (2010). Parameters influencing full scale sublevel caving material recovery at the Ridgeway gold mine. *International Journal of Rock Mechanics and Mining Sciences*, Vol 47, issue 4 June 2010, pp. 647-656.
- Campbell, A. D. (2018). Effects of blast ring burden and explosive density on fragmentation and ore recovery in sublevel cave mines. In *Caving 2018: Proceedings of the Fourth International Symposium on Block and Sublevel Caving* (pp. 457-470). Australian Centre for Geomechanics.
- DeGagne, D. O. (2005). The Influence of Blasting Fragmentation on Ore Recovery in Sublevel Cave Mines. In *ARMA US Rock Mechanics/Geomechanics Symposium* (pp. ARMA-05). ARMA.
- Kozicki, J. & Donze, F. V. (2009). YADE-OPEN DEM: An open-source software using a discrete element method to simulate granular material. *Engineering Computations*, 26(7), 786-805.
- Kvapil, R. (1992). Sublevel caving. *SME mining engineering handbook*, 2, 1789-1814.
- Lapčević, V. & Torbica, S. (2017). Numerical investigation of caved rock mass friction and fragmentation change influence on gravity flow formation in sublevel caving. *Minerals*, 7(4), 56.
- Lapčević, V., Torbica, S., Stojanović, M. & Vojinović, I. (2023). Development and Validation of Universal 3D Blast Fragmentation Model. *Applied Sciences*, 13(14), 8316.
- Lith, A., Kuchta, M. & Quinteiro, C. (2004). Prediction of fragmentation for ring blasting in large-scale sublevel caving. In *Proceedings of 13th International Symposium on Mine Planning and Equipment Selection (MPES 2004)*, Wrocław, Poland, CRC Press/Balkema (pp. 257-268).

- Manzoor, S., Gustafson, A., Schunnesson, H., Tariq, M. & Wettainen, T. (2022). Rock fragmentation measurements in sublevel caving: field tests at LKAB's Malmberget mine. In *Caving 2022-Fifth International Conference on Block and Sublevel Caving*, Adelaide, Australia, August 30-September 1, 2022 (pp. 381-392). Australian Centre for Geomechanics.
- McNeel, R. & others. (2010). Rhinoceros 3D, Version 6.0. Robert McNeel & Associates, Seattle, WA.
- Yi, C., Johansson, D., Wimmer, M., Nordqvist, A. & San Miguel, C. R. (2022). Numerical modelling of fragmentation by blasting and gravity flow in sublevel caving mines. In *Caving 2022-Fifth International Conference on Block and Sublevel Caving*, Adelaide, Australia, August 30-September 1, 2022. Australian Centre for Geomechanics.
- Yi, C., Sjöberg, J. & Johansson, D. (2017). Numerical modelling for blast-induced fragmentation in sublevel caving mines. *Tunnelling and Underground Space Technology*, 68, 167-173.
- Zhang, Z. X. & Wimmer, M. (2018). A case study of dividing a single blast into two parts in sublevel caving. *International Journal of Rock Mechanics and Mining Sciences*, 104, 84-93.