

Investigating the energy balance of two mining methods set in a deep underground metal mine in the U.S.

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ABSTRACT: Hecla Mining Company (Hecla) operates the Lucky Friday Mine since 1958, which is an underground silver, lead, and zinc mine near Mullan, Idaho, USA. In the mid-1980s until 2020, the company relied on the Lucky Friday Underhand Longwall (LFUL) method for seismic control to mine (first) the Lucky Friday and (then) the Gold Hunter ore bodies. However, engineering challenges related to high in-situ rock stresses, squeezing ground conditions and seismic occurrences continued to increase as the production levels deepened to depths greater than 2,000 m below ground surface. In 2020, Hecla developed a new mining method called UCB (Underhand Closed Bench) which proactively induces fault slip in proximity of the mining front, improving safety and productivity at the mine. UCB was fully implemented at the Gold Hunter in 2021. Although preventing faults to slip at their critical load was identified as the main seismic control measure, the contribution of fragmented ore presents another component capable of reducing the seismic energy release measured at the mine. As part of the seismic hazard research initiative, the National Institute for Occupational Safety and Health (NIOSH) collaborated with Hecla to develop a series of numerical models using a 3-dimensional distinct element method (3DEC) to quantitatively investigate and compare the differences in the energy balance characteristics between the LFUL and the UCB methods. As a result, the numerical models were sensitive enough to capture the differences between the mining methods and were in good agreement with the field observations, recognizing the influence of blasted ore in seismic control.

1. INTRODUCTION

As part of the project, managing ground support for long-term stability, the National Institute for Occupational Safety and Health (NIOSH), is researching more effective seismic energy analysis methods and improved forecasting of induced seismicity around mining areas. The Lucky Friday Mine (Hecla) has recently implemented a new mining method, Underhand Closed Bench (UCB), that has yielded favorable results regarding seismic energy release and control when compared to the Lucky Friday Underhand Longwall method (Board et al., 2022; Armatys, 2023). This collaborative opportunity was realized and leveraged NIOSH's modeling expertise and Hecla's proprietary mining method, which is beneficial for both parties.

Past research by Kim et al. (2020) showed methods by which numerical modeling could be used to estimate rock bursting as a function of the mining method. In a drill-and-blast excavation, there is often an annulus of damaged rock in which both the strength and the modulus are reduced relative to the original values, the reduction being dependent on the quality of the blasting. Hence, it is possible that the blast damage creates a more favorable state with respect to bursting, particularly in comparison

to the undamaged wall of a mechanized excavation. The modulus in the damage zone due to blasting can be reduced by as much as 25~50% of the original modulus of the rock mass as a function of the excavation method and stress condition.

This study assesses the energy balance of two different mining methods for the same geometrical extraction using 3DEC (Itasca Consulting Group, 2024). Literature from Jaeger et al. (2005), Hedley (1992) and Salamon (1974; 1984) addresses the energy balance in the rock mass, defining the energy balance components and demonstrating that the energy release depends on the mining size leading to the completion of an underground excavation in an elastic medium. The explanation of the complex formulas of energy balance is not the main subject of this paper, so readers should refer to the references provided above for more information.

The first mining method is the Lucky Friday Underhand Longwall (LFUL), which is a traditional underhand cut-and-fill mining method that relies on drilling-and-blasting to extract incrementally, on 2.5 m advance by 3 m high, a narrow horizontal cut, typically 3.0–3.6 m wide, along the vein until completion and backfilled with cemented paste. The next (lower) cut progresses under engineered fill, similarly, extending the mining front deeper by ~3 m. The

second mining method is the UCB, which utilizes a bulk mining technique where a single extracted cut serves as the drilling horizon and the initial draw point. Therefore, a series of blast hole rings are drilled blind into the floor (without break-through) to target ~ 8.5 m of vertical ore along ~ 76 m of vein strike. The UCB blast fragments the rock while generating notable stope closure and induces a seismic response. After a seismic delay, operation proceeds to muck out the swelled rock to the original floor elevation of the drill cut. After backfilling the top cut, operation mines underhand the fragmented ore in two 4.5 m high subsequent cuts, backfilling each cut on completion, with little to no secondary cut-and-fill blasting*. The UCB blasting cycle repeats on the second (lowest) cut, which serves as the new drilling horizon for the next blast. The geometrical volume of extracted ore is comparable between methods; however, the extraction rate and the mined material differs (i.e., mining through intact vs fragmented ore). The incremental LFUL blasts are also relatively small when compared to the bulk blast of UCB. Thus, instead of blasting each in-stope LFUL face twice per day, the entire UCB stope is blasted instantaneously once every two months or so with a very large blast. Internal studies to Hecla have identified a reduction in seismic energy release in proximity of stopes for UCB when compared to LFUL (for equivalent ore volume) as measured by their local seismic system (Board et al., 2022), and have successfully modeled induced fault slip as the main seismic control feature of the new method where critically-oriented structures in proximity of the stopping area slip before reaching their critical shear state (Armatys, 2023). This study will further investigate the energy balance of the LFUL and the UCB mining methods with attention to the fragmented ore to quantify its seismic control potential.

The following section introduces the numerical modeling approach, including assumptions and conditions. The third section describes the methodologies used to evaluate the effects of mining-induced seismicity in each method which are modeled by means of a DFN (Discrete Fracture Network) in 3DEC.

2. UNDERGROUND MINING METHODS SIMULATION USING DFN AND 3DEC MODELING TECHNIQUES

A 3DEC model with dimensions of 120 m (W) \times 117 m (H) \times 10 m (L) was constructed as illustrated in Fig. 1 and Fig. 2. We assumed a discontinuous thin-slit structure reproducing a standard stope with an inset of pillars. The vein discontinuity was reproduced by rotating it 110° from the north in the model (i.e., the strike of the vein). We replicated a mining configuration by assuming a fixed geometry and varying the stope extraction by method in the numerical model. The depth of the top boundary of the

model from the surface was assumed to be 2,167 m below ground. In the stope, 25 previous (mined out) cuts and 3 consecutive (unmined) cuts were constructed with a height of 3 m and a width of 3 m. A 10 m high pillar above the previous cuts was also considered in the model. The model was divided into two regions for a relatively fine mesh in the middle of the model. The zone size was 0.6 m in the middle and 10 m in the rest of the model, respectively. As a result, the 3DEC model had approximately 1,160,000 zones in 39,700 blocks.

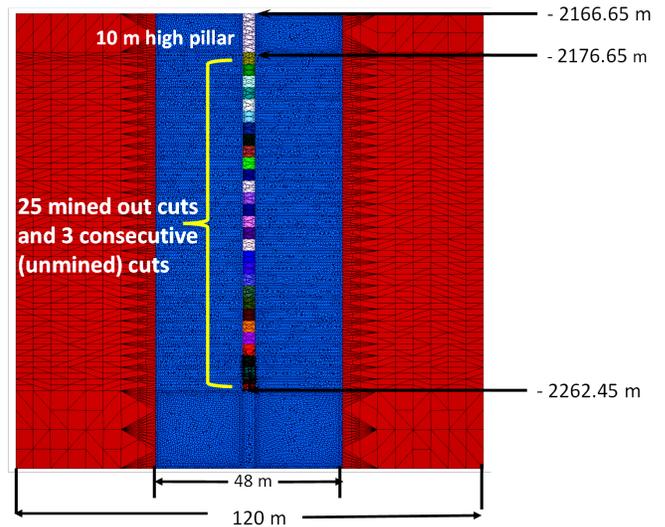


Fig. 1. 3DEC model layout in cross-section.

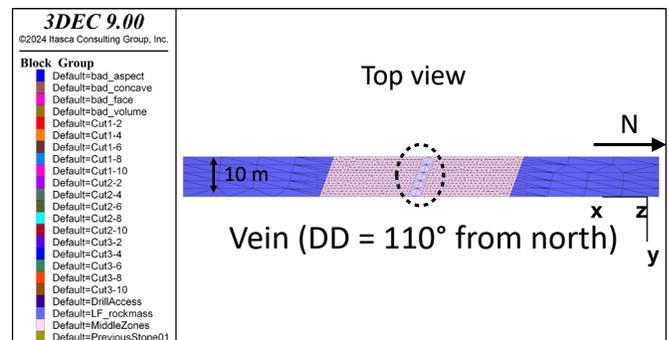


Fig. 2. 3DEC model layout in top plan-view.

Fig. 3 presents the loading and the boundary conditions. A surcharge of vertical stress was applied on the top boundary of the model to account for the weight of the overburden not represented in the model. The horizontal stresses are greater than the vertical stress. It was input that the major principal stress (σ_H) had a magnitude (MPa) of $1.5 \times$ overburden stress in the x-direction of the model (i.e., oriented north-south). The intermediate principal stress (σ_h) has a magnitude (MPa) of $1.2 \times$ overburden stress in the y-direction of the model (i.e., oriented east-west). Although these were slightly different orientations from the field measurements (Whyatt and Beus, 1995), modifications were needed to simplify the model for this

* <https://www.youtube.com/watch?v=jN7szlFt4Ei>

study. The minor principal stress (σ_v) had a magnitude (MPa) of the unit weight \times depth.

For the boundary conditions, both sides of the model were fixed in the x-direction, while the front and the back were fixed in the y-direction. The bottom of the model was fixed in the z-direction (i.e., vertical direction).

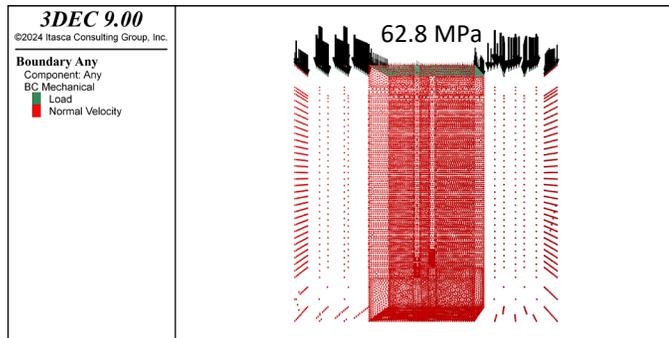


Fig. 3. Loading and boundary conditions for 3DEC model.

The Hoek-Brown constitutive model was applied to the rock mass, and the Mohr-Coulomb model was considered for the cut-and-fill in stope extraction to simulate backfill.

The intact unconfined compressive strength and m_i (Hoek-Brown criterion parameter) for the rock mass were estimated as 109 MPa and 27, respectively. Based on the Geological Strength Index (GSI) 60, the rock mass modulus was estimated to be 29.4 GPa by reducing the intact rock modulus of 56.6 GPa using the rock mass properties estimation logics proposed by Hoek et al. (2002). The Poisson's ratio and the unit weight of the rock were considered as 0.2 and 0.029 MN/m³, respectively. Backfill was simulated using Mohr-Coulomb, assuming material properties found in literature (by Johnson et al., 2015).

Table 1 shows the material properties used for the rock mass and the backfill in this model.

Table 1. Material properties used for 3DEC model.

Input parameter	Value
Unit weight (MN/m ³)	0.029
Intact Unconfined Compressive Strength (UCS) (MPa)	109
Intact Hoek-Brown constant, m_i	27
Poisson's ratio	0.2
Intact Young's modulus (GPa)	56.6
Geological Strength Index	60
Backfill UCS (MPa)	4.15
Backfill tensile strength (MPa)	0.47
Backfill Young's modulus (GPa)	1.1
Backfill Poisson's ratio	0.17

Fig. 4 shows the incremental excavation phase of the cut. Each cut is 3 m high, and the length of each advance step is 2 m from the front to the back, respectively.

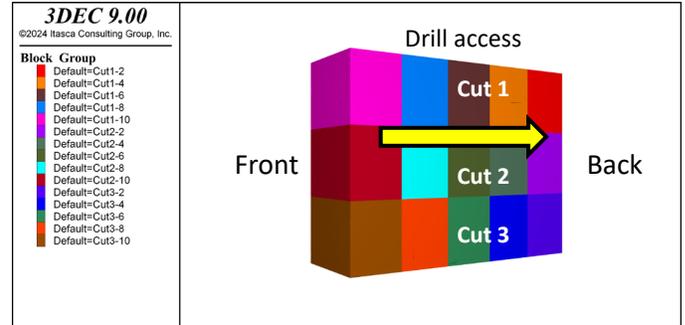


Fig. 4. Explicit and incremental excavation phase in cuts.

The key objective of this study is to compare the energy balance between the two different mining methods released within a mining block. The LFUL method continuously and gradually removes material from each consecutive (unmined) cut, while the UCB first fragments and then excavates each cut. Therefore, all assumptions and conditions for the extraction of the cuts in both the LFUL and the UCB mining methods should be as representative of reality as possible. To achieve this goal, all blocks of the three cuts were built using the Bonded Block Model (BBM) technique. The BBM associated with a DFN can represent fractured/blasted material (Itasca, 2019). It can be used to simulate intact vein material or the rock mass as bonded polyhedral elements. These bonded polyhedral blocks can break apart along their subcontacts (bonds) when overstressed, simulating the initiation of cracks that can coalesce and/or propagate to fracture the rock mass. This results in an emergent damage pattern with associated bulking. The BBM in the undercuts initially consisted of deformable elastic blocks surrounded by elastic joints. The elastic joint was instantaneously changed to a Mohr-Coulomb joint to mimic the fragmentation after drill access excavation.

The built-in DFN generator in 3DEC was used to simulate explicitly the fragmentation observed in the lower cuts during UCB. A random orientation of three orthogonal discontinuity sets was used to generate the DFN. Fig. 5 shows the fractures within the mining block to simulate ore fragmentation.



Fig. 5. Rock blocks system created by DFNs to simulate fragmentation of cuts.

For the LFUL case, these blocks surrounded by elastic contacts are assumed to act as unfragmented groups until the calculation is complete. On the other hand, for the UCB case, the constitutive model of the contacts remains elastic as in the LFUL case until the drill access is

excavated and then it changes to the Elasto-Plastic Mohr-Coulomb model representing fragmentation.

Table 2 compares the three mining cuts, as shown in Fig. 5, model construction logic between the LFUL and the UCB mining methods.

Table 2. Summary of logic to construct three mining cuts, as shown in Fig. 5, for two different mining methods in the 3DEC model.

	LFUL	UCB
Blocks	Deformable and elastic	Deformable and elastic
Joints (contacts)	Elastic	Elasto-plastic (Mohr-Coulomb)
Blocks moduli	Same as rock mass	Same as rock mass
Joints normal and shear stiffnesses	Equivalent to rock mass	Equivalent to rock mass
Joints shear strength	N/A	Zero cohesion, zero tensile strength, and a non-uniform friction angle applied depending on the depth of 3 consecutive undercut
Excavation process (initial in-situ stress stage) was calculated, followed by the 25 mined cut-and-filled cuts and the drill access excavation.	After the drill access excavation, the first 2 m long cut in Cut 1 was immediately removed.	After the drill access excavation, elastic joints changed into Mohr-Coulomb joints and the model ran to reach equilibrium for achieving stress relaxation associated with fragmentation. Then a 2 m long cut in Cut 1 was removed
Execution and calibration	Either 2 m advance excavation continued until a ~8 cm closure was observed in the drill access was simulated or until the equilibrium convergence criteria of $1e^{-5}$ was reached.	Either 2 m advance excavation continued until (i) a ~8 cm closure was observed in the drill access as fragmentation and under each cut in Cut 1, (ii) ~15 cm closure in the drill access in Cut 2 and 3, or until the equilibrium convergence criteria of $1e^{-5}$ was reached

3. RESULTS AND DISCUSSION

The initial cut-and-fill mining portions for both the LFUL and the UCB models were carried out in 3DEC independently.

Fig. 6 shows the total displacement of the blocks after the drill access excavation was completed, before removing the three consecutive vertical cuts. A high displacement of approximately 4.5 cm occurs in the center of the stope along the previous mined-out cuts.

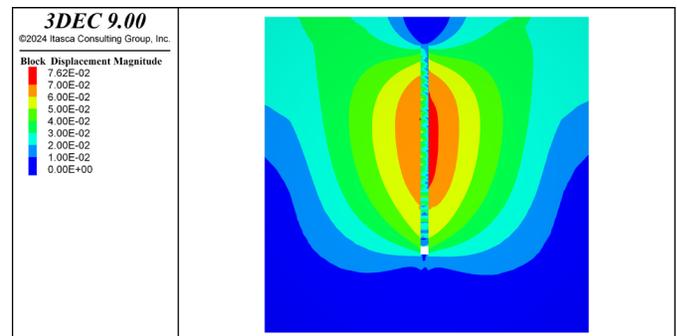


Fig. 6. Total displacement (m) contours after the drill access are established.

Fig. 7 presents the mining-induced major principal stress (σ_1) contours before excavating the three bottom cuts. The σ_1 is concentrated at the top and bottom of the previous cut, confirming that the cut-and-fill process of the stope was well simulated in the 3DEC model using the initial conditions before proceeding to “mine” the three consecutive vertical cuts by LFUL and UCB.

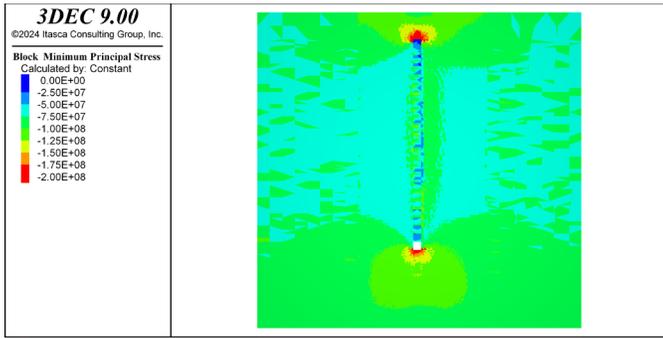
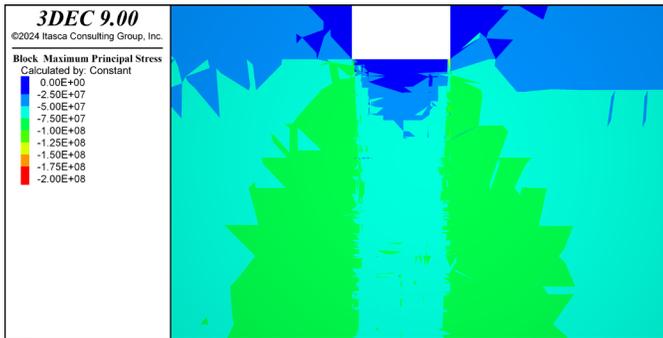
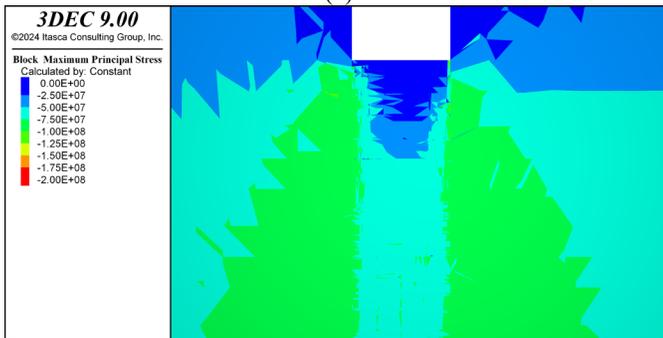


Fig. 7. Major principal stress (Pa) contours after drill access excavation.

Fig. 8 (a) and (b) illustrate mining-induced minor principal stress (σ_3) contours in the step before removal of the three consecutive vertical cuts in the case of LFUL and UCB, respectively. Note that Fig. 10 (a) shows the σ_3 contour before the first cut excavation and after drill access excavation. However, Fig. 10 (b) indicates the σ_3 contour before the first cut excavation and after drill access excavation and blasting (fragmentation) simulation. The stress relaxation zones due to the excavation are contoured in blue. The depth of the stress relaxation zones at the bottom of the drill access in the case of UCB (after fragmenting the floor) appears to be greater than that registered in the LFUL simulation.



(a)



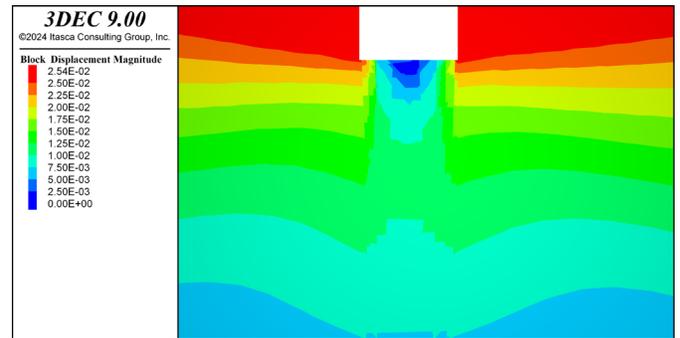
(b)

Fig. 8. Minor principal stress (Pa) contours before cuts excavation, (a) LFUL and (b) UCB (after simulating blast fragmentation).

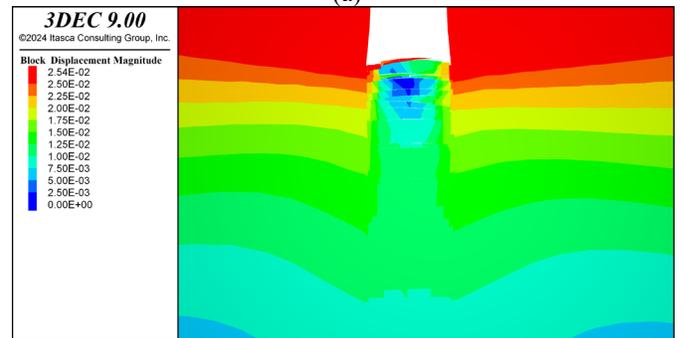
Fig. 9 (a) and (b) show the vertical displacement contours in the step before removal of the three consecutive vertical cuts by the LFUL and the UCB cases, respectively.

In the case of LFUL as shown in Fig. 9 (a), the maximum vertical displacement on the floor of the drill access was less than 1.5 cm. On the other hand, as illustrated in Fig. 9 (b), the maximum vertical displacement was greater than 8.2 cm, which reflects the swell observed in the drill cut after a UCB blast (although noticeably less than in practice, which can reach the back).

Considering the results of Fig. 8 and Fig. 9, the differences between the two mining methods with and without the fragmentation process described in Table 1 were crudely captured in these models.



(a)



(b)

Fig. 9. Vertical displacement (m) contours before cut excavation, (a) LFUL and (b) UCB (after simulating blast fragmentation).

Since we confirmed that the difference between the two mining methods matches crudely with field observations, the next step was to extract (mine) the three consecutive cuts to compare how the energy release differs between each mining method.

Fig. 10 (a) and (b) indicate the total energy released versus the time-step as a function of mining the cuts per LFUL and UCB, respectively. The energy release was calculated by the built-in energy calculator in 3DEC (Itasca, 2024). Note that the scale of the x and y axes in the two figures are the same.

The stepwise curve from time-step zero to 3.2×10^4 represents the total energy released during the previous mine-wide extraction. In the case of LFUL, as shown in Fig. 10 (a), the total energy released when mining the subsequent three cuts continued to increase exponentially from the moment the first cut was removed. In the case of UCB, as shown in Fig. 10 (b), the total energy released

when mining the subsequent three cuts is represented by three well-defined stepped curves. In addition, the maximum value of the energy released at the end of the extraction was approximately 20% lower in the case of UCB than in the case of LFUL.

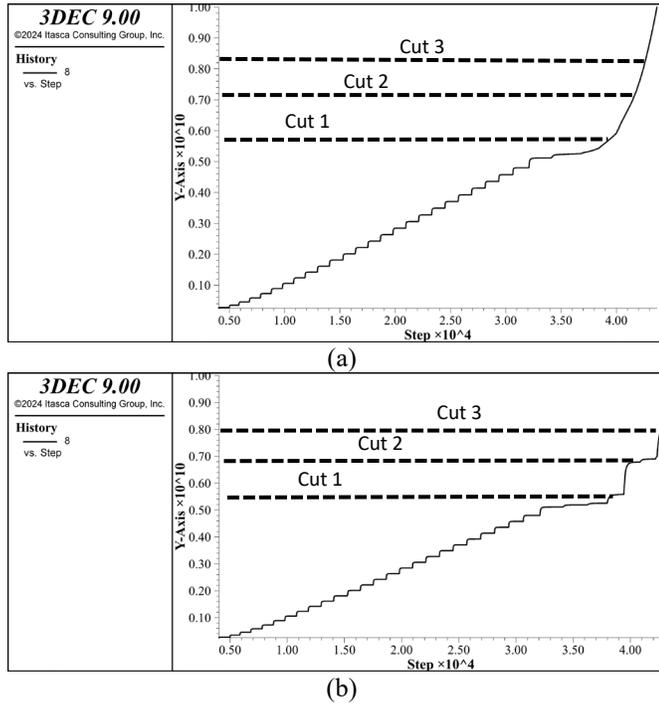


Fig. 10. Total energy released versus time-step, (a) LFUL; (b) UCB.

Fig. 11 provides the details of the energy calculation per step (or cut extraction) by separating the total energy released into each energy component. Note that the Figure's y-axis of the bar chart assumes the logarithmic scale. The most interesting finding here is that the kinetic energy release, often correlated with recorded seismic energy (Hedley, 1992), for UCB is noticeably less compared to LFUL, a reduction from 35% to 47% as shown by the blue bars in the figure. This is consistent with field observations provided by Board et al. (2022).

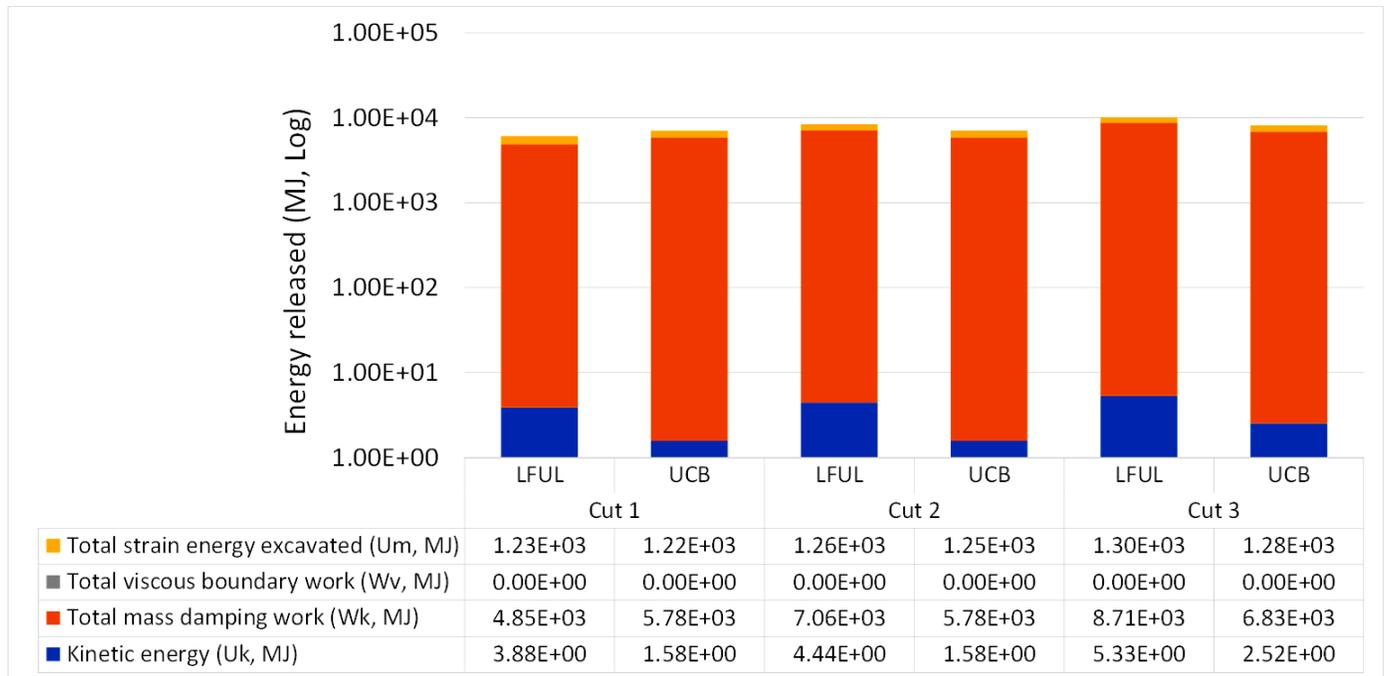


Fig. 11. Detailed comparison of each energy component between LFUL and UCB.

4. CONCLUSIONS

As part of researching methods to reduce seismic hazard, the National Institute for Occupational Safety and Health (NIOSH) collaborated with Hecla Mining in this study by

developing a series of numerical models using a 3-dimensional distinct element code (3DEC) to quantitatively investigate and compare the differences in the energy balance characteristics between the LFUL and the UCB mining methods. The cut-and-fill and the bulk

mining were replicated by the incremental and explicit process in the model. The fragmentation process resulting from UCB blasts was simulated using the Bonded Block Model in conjunction with the Discrete Fracture Network technique. As a result, the tensile stress relaxation and plastic yield zones developments due to the fragmentation process in the UCB appeared more pronounced than those of the LFUL. The total energy released during UCB was about 20% less than that of the LFUL, inferring the seismic control potential offered by the fragmented ore.

In future research, additional numerical analysis could be performed considering major fault planes in the mine that were ignored in this paper to simplify the 3DEC model.

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DISCLAIMER

The findings and conclusions in this report are those of the author(s) and do not necessarily represent the views of the National Institute for Occupational Safety and Health, nor those of Hecla Mining Company. Mention of any company or product does not constitute endorsement by NIOSH.

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