

Numerical modelling of fragmentation by blasting and gravity flow in sublevel caving mines

C Yi *Luleå University of Technology, Sweden*

D Johansson *Luleå University of Technology, Sweden*

M Wimmer *LKAB, Sweden*

A Nordqvist *LKAB, Sweden*

CR San Miguel *Luleå University of Technology, Sweden*

Abstract

The sublevel caving (SLC) mining method is based on the utilisation of gravity flow of blasted ore and caved waste rock. Blasting is the initial and the major impact upon primary fragmentation and later material flow characteristics. A coupled numerical model was employed to investigate the fragmentation due to blasting and the gravity flow using the LS-DYNA code. In the coupled model, a loose discrete element model (DEM) was used to represent caved waste rock and a bonded DEM model was used to represent the orebody to be blasted, a particle blast method (PBM) was used to describe the detonation of explosive and a finite element model (FEM) was used to model the remaining orebody. The cumulative dilution of the ore by waste during extraction was evaluated. The results showed that the fragments at the upper part of the ring are coarse while the fragments at the lower part of the ring are fine. The change of the cumulative dilution along with the extraction is reasonable.

Keywords: *sublevel caving, fragmentation by blasting, gravity flow, numerical modelling*

1 Introduction

Sublevel caving (SLC) is an advanced and highly efficient low-cost bulk underground mining method that provides early access to ore. It is based on creating cavities in the orebody and allowing the ore fragmented by blasting to fall to underlying levels by means of gravity. When the ore is extracted, the waste rock collapses by gravity and automatically fills the cavity. A major disadvantage of SLC is the relatively high dilution of the ore by waste. A major factor influencing this dilution is the flow behaviour of the fragmented ore and waste material (Susaeta 2004). Blasting has been identified as having the initial and the major impact on primary fragmentation and subsequently on fragmented ore flow characteristics (Brunton 2009).

SLC mines have the most intensive blasting process of all the mining methods, as generally one or two rings are fired at a time at each drawpoint to maximise recovery and reduce dilution. Proper fragmentation of the ore ring in mines which apply this method is important for ore recovery. In SLC, blasting takes place in a semi-confined situation, where the blasted material can swell due to the compaction of the caved material and, to a minor extent, swell into the void volume of the production drift (Wimmer 2010). The swelling is encouraged for achieving a well fragmented burden with sufficient porosity, which is crucial for fragmentation. Simultaneously, the caved masses ahead should be well compacted. This will finally determine the actual flow behaviour of fragmented ore and waste.

Several analytical and empirical models have been developed in the past, where the interaction of semi-confined blasting conditions, SLC blast design and rock mass characteristics on blast performance were investigated (Brunton 2009). Due to the complexity and costs involved, only a few full-scale SLC draw marker trials have been conducted in the past. The detailed full-scale experiments have been conducted at Ridgeway with over 70 individual trials to assess the impact of drill and blast parameters on material recovery (Power

2004; Brunton 2009). Full-scale experiments were conducted at the Ernest Henry Mine to measure the effect of crosscut height on recovery and depth of draw (Campbell 2018). Petropoulos et al. (2018) investigated the behaviour of the blasted material in confined conditions, as well as the behaviour of the confining materials, in the Kiruna Mine. The results showed that the finer confining material showed a steeper angle of repose after the blast, which shows a higher friction coefficient than found in the coarser confining material. Investigation on the gravity flow in the Kiruna Mine showed that the gravity flow might often be of disturbed character (Wimmer et al. 2015; Nordqvist & Wimmer 2016). The effect of confinement was studied in a pillar test in the Kiruna mine by Newman (1996). The scope of the test was to study the ore swell and to estimate the amount of blast damage in an SLC production ring blast.

Numerical modelling has been an important tool in investigating the blast and gravity flow in SLC mines. Brunton & Chitombo (2010) numerically investigated the impact of SLC blast design and performance on material recovery at the Ridgeway SLC operation. Their results showed that significant rock mass damage occurred in the vicinity of the blastholes detonated on the first delay. This resulted in severe damage to holes detonated on the second delay and rock mass dislocation and damage in front of these holes. Yi & Johansson (2014) numerically compared the blast-induced fragmentation of curved-holes and standard SLC rings by using the 'Blo-up' code (Furtney et al. 2009). The purpose was to investigate the benefit of applying curved holes in LKAB's underground mines to equalise the specific energy and hence achieve better fragmentation. Yi et al. (2017) then investigated the effects of delay time and the location of the detonator on fragmentation for the Malmberget mine using the LS-DYNA code (Hallquist 2016). Furthermore, Selldén & Pierce (2004) investigated the gravity flow behaviour in SLC with the PFC3D code (Itasca Consulting Group 2015). Different degrees of disturbed flow were modelled in this investigation and the obtained dilution entry curves resembled those reported from the field. DeGagne & McKinnon (2005, 2006) used the PFC3D code to simulate the gravity flow with different ore size models. The models displayed recovery and dilution characteristics comparable to classical Kvapil curves (Kvapil 1998) and offer the potential for comparison with field data. Furthermore, Sharrock et al. (2004) presented a cellular automata (CA) model to simulate the gravity flow in SLC. Additionally, Castro et al. (2009) developed a FlowSim code based on a new CA logic. This code is based on geometrical parameters and a transition function to simulate the flow in unconfined and confined conditions. Campbell and Power (2017) used the CA flow software and a blast mobility factor to calibrate a flow model using measured marker recovery and to calibrate flow and recovery at a ring scale. Lapcevic & Torbica (2017) numerically investigated the caved rock mass friction and fragmentation change influence on the gravity flow formation in sublevel caving with 'Yade' code (Šmilauer 2020).

Considering the definition of SLC described above, the earlier numerical investigations provide insights into the fragmentation and gravity flow in this mining method. However, existing numerical studies are focused on either fragmentation by blasting or gravity flow. To properly evaluate the impact of the blast on the gravity flow, simulating both fragmentation by blasting and gravity flow processes with one model would be advantageous. Furthermore, it is important to understand the fragmentation in combination with porosity due to blasting under semi-confined blasting conditions and the behaviour of gravity flow of the blasted ore and the waste rock. This paper details how the LS-DYNA code was employed to model both blasting and gravity flow in one model.

2 Numerical modelling with LS-DYNA

In the numerical model, a bonded particle model (BPM) is used to model an intact ore body to be blasted and a loose particle model (LPM) is used to model the caved waste rock which provides a confined environment for the ore body to be blasted. The remaining ore body after blasting is modelled with finite element method (FEM). The detonation of explosives in the blast hole is modelled with the particle blast method (PBM). A numerical model was built based on the design of SLC at the Kiruna mine, Sweden.

2.1 Discrete element method and particle blast method in LS-DYNA

A loose particle model and the contact between loose particles are shown in Figure 1. As can be seen from Figure 1b, two springs are used to describe the normal and shear forces between the particles. Two dashpots are used to model friction damping during sliding in normal and shear directions. For wet loose particles, the capillary force between particles is described with a liquid bridge.

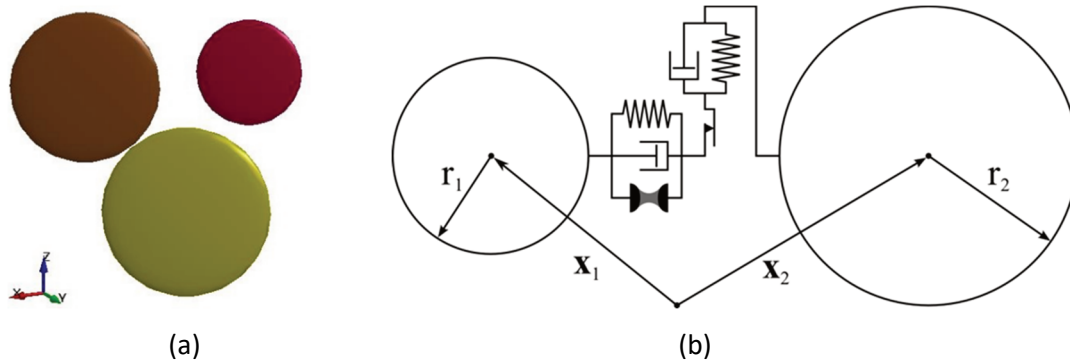


Figure 1 Loose particles and the contact between particles (after Karajan et al. 2013). (a) Loose particles; (b) Contact between loose particles

A bonded particle model is shown in Figure 2, in which all particles are linked to their neighbouring particles through bonds. Bonds represent the complete mechanical behaviour of solid mechanics. Every bond is subjected to tension, shearing, bending, and twisting. In a BPM, crack nucleation is simulated through the breaking of internal bonds while fracture propagation is obtained by coalescence of multiple bond breakages. As a result of the simulated fracturing process, blocks of arbitrary shapes can form and can subsequently interact with each other.

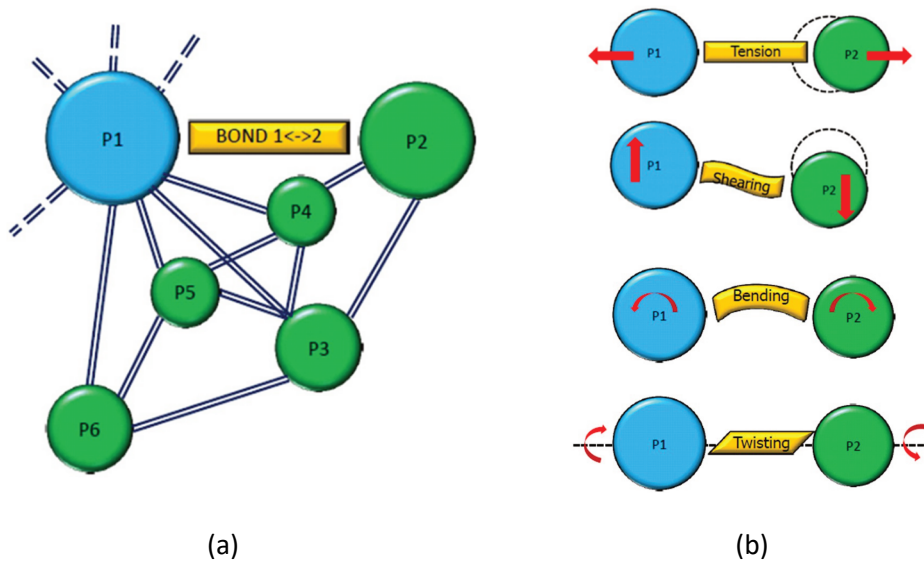


Figure 2 Bonded particle model and possible force and moment transmission modes between two bonded particles (after Karajan et al. 2013). (a) Bonded particles; (b) Possible force and moment transmission

The detonation of explosives is described by the particle blast method. The particle blast method is an extension of the corpuscular particle method (CPM), which is a coarse-grained multi-scale method for gas dynamics simulation. The particle blast method improves CPM so that it can simulate real gas law with high pressure and high temperature. A co-volume effect is introduced in this method to better characterise gas behaviour at extreme pressure. For an efficient contact treatment, the particles are given a spherical shape. The particle-structure interactions are purely elastic collisions. Each of the particles has translational energy and spin energy. The balance between translational energy and spin energy is determined directly from the heat capacities. With this, and by grouping many molecules as one particle, the particle blast method reduces the degree of freedom of the system by several orders of magnitude (Teng & Wang 2014).

2.2 Numerical models and parameters

The model for a standard ring is shown in Figure 3a. The green part in Figure 3a is the remaining orebody after blasting. It is discretised into solid finite elements. The red part and the blue part in Figure 3a are discretised into shell finite elements to supply confinement for particles inside. Since the remaining orebody has insignificant effect on the gravity flow of ore, it is treated as a rigid body to provide a boundary for the explosive and the orebody to be broken. The inside of the model is shown in Figure 3b. The outside shell elements and solid elements are set as transparent to see the inside of the model. The orebody to be blasted is represented by bonded particles. The thickness of the orebody to be blasted is 3.5 m which matches the blast ring burden of 3.5 m used at the Kiruna Mine. The waste particles radius ranged between 0.30–0.45 m while the radius of ore particles is 0.24 m. The width of the drift is 7 m and the height is 5.2 m. The dump angle of the ring is 10°.

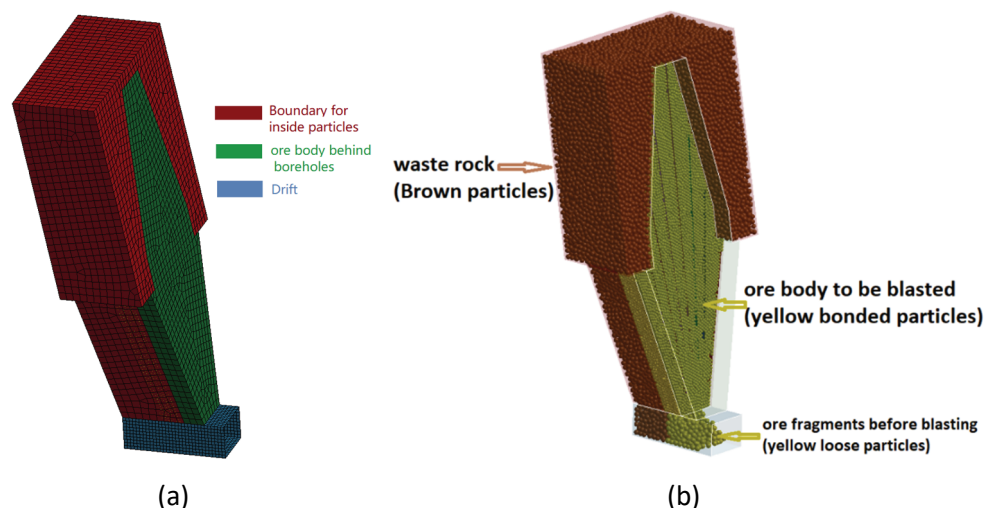


Figure 3 The numerical model in LS-DYNA. (a) Overall view of the numerical model; (b) Inside of the model

The charge pattern in the Kiruna Mine and its numerical model are shown in Figure 4. There are eight blastholes in one ring and the length range of the blastholes is between 23.3–51.5 m. The borehole diameter is 115 mm. The firing pattern is designed to open symmetrically from the two centre holes of the ring with delay intervals of 25 ms (Wimmer 2012). In practice, the holes are top-initiated with redundant lower primers set at +25 ms, see Figure 4a. In the numerical model, only the top initiation point is defined in each borehole, the initiation sequence is the same as that in Figure 4a.

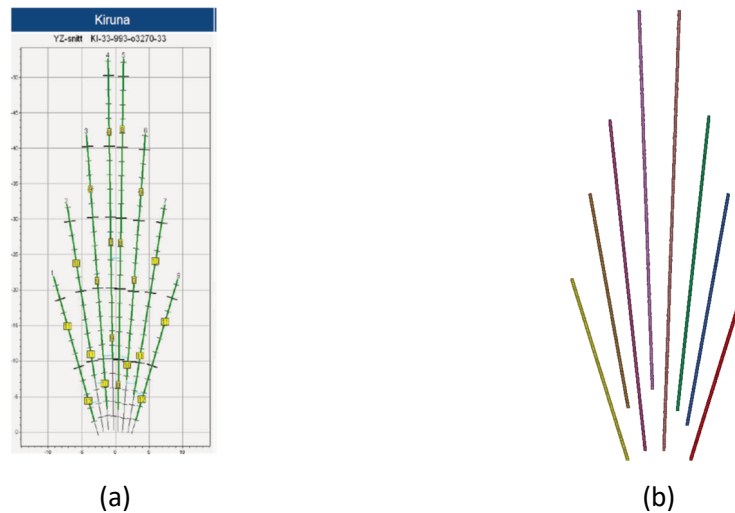


Figure 4 Charge pattern. (a) Charge pattern in Kiruna Mine; (b) Charge pattern in the numerical model

A summary of the particle properties and parameters is in Table 1.

Table 1 Particle properties of ore and waste rock

Parameter	Value
Density of ore	4,700 kg/m ³
Young's modulus of ore	65 GPa
Density of waste	2,800 kg/m ³
Young's modulus of waste	70 GPa
Tensile strength of bond	20 MPa
Shear strength of bond	40 MPa
Particle radius of ore	0.24 m
Particle radius of waste rock	0.3–0.45 m

The parameters used in the particle blast method of the explosive are shown in Table 2, in which, D refers to the detonation velocity, γ is the ratio of the heat capacity at constant pressure (C_p) to heat capacity at constant volume (C_v), ρ is density, E is the explosive energy per unit volume and b is the Co-volume coefficient of the explosive.

Table 2 Parameters of explosive

D (m/s)	γ	ρ (Kg/m ³)	E (J/m ³)	b
5,200	1.5	1,200	3.8E9	0.62

3 Numerical modelling results

3.1 Blast induced fragmentation

The detonation process of explosives in the middle two boreholes is shown in Figure 5.

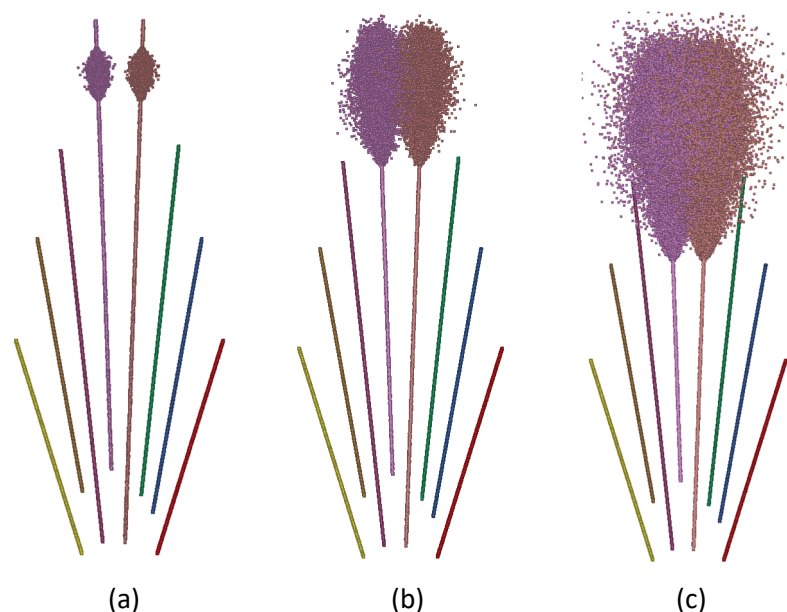


Figure 5 The detonation process of explosives in the middle two boreholes. (a) $t = 0.5$ ms; (b) $t = 1.5$ ms; (c) $t = 3.0$ ms

Figure 6 shows the blast-induced damage in the orebody from different viewing angles. In Figure 6b, the particles for waste rock are hidden. For each particle in a BPM in LS-DYNA, the damage is defined as the ratio of broken bonds to total bonds. For a specified particle, the damage value of one shows that all bonds of the particle are broken, and the damage value of zero indicates that no bonds of the particle are broken. The bond breakage induces crack propagation in the orebody and breaks it into fragments in different shapes and sizes.

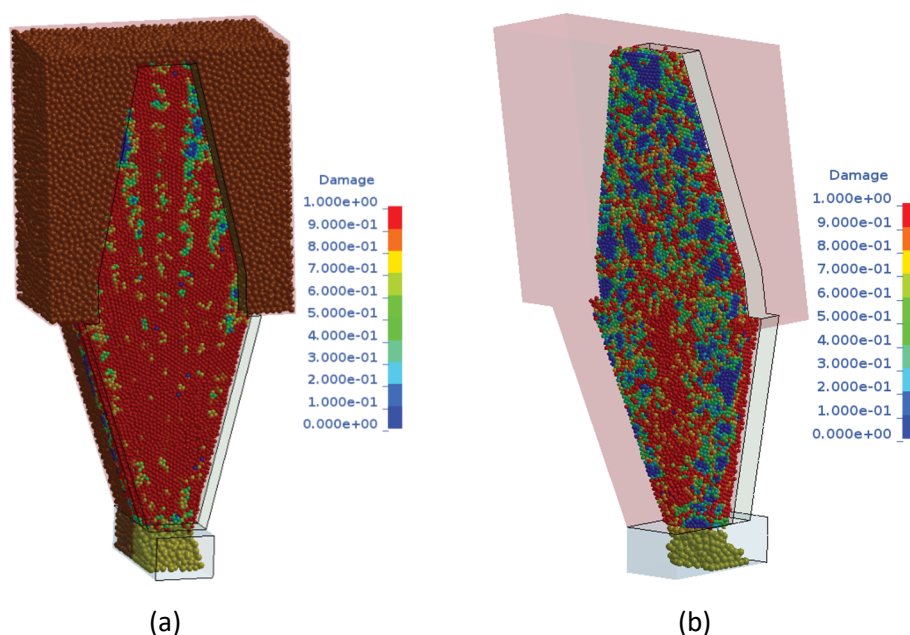


Figure 6 Blast-induced damage in the model at 0.1 s. (a) View from footwall; (b) View from hanging wall

Figure 6 also shows that the fragments are finer at the lower part of the ring and in contrast, the fragments are coarser at the upper portion.

To see the fragmentation inside of the ring, three section profiles at different burden depths are shown in Figure 7. The burden depth in Figure 7 is the distance from the selected section to the section of the blastholes, i.e. Figure 7a refers to the blasted ore/waste interface. Figure 7 shows that the fragment size increases with the distance to the blastholes. Similar results were observed by Brunton (2009).

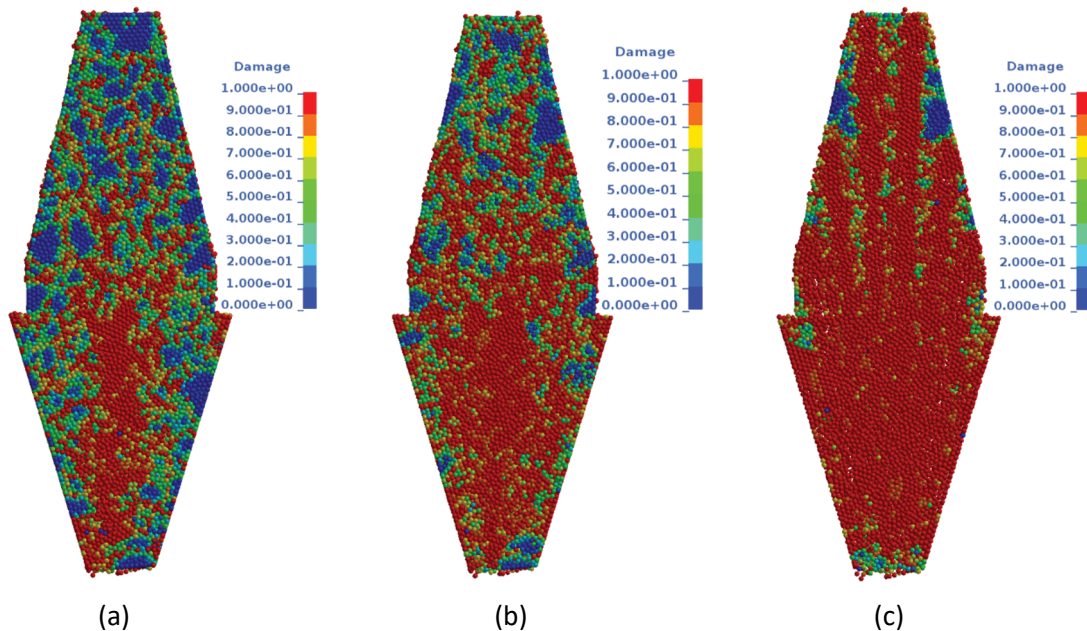


Figure 7 Fragmentation at different burden depths inside of the ring at 0.1 s. (a) Depth = 3.5 m; (b) Depth = 2.5 m; (c) Depth = 1.5 m

3.2 Gravity flow of ore after blasting

After blasting, the extraction process is simulated. Figure 8 shows the flow-out process of fragmented ore and waste at different extraction rates.

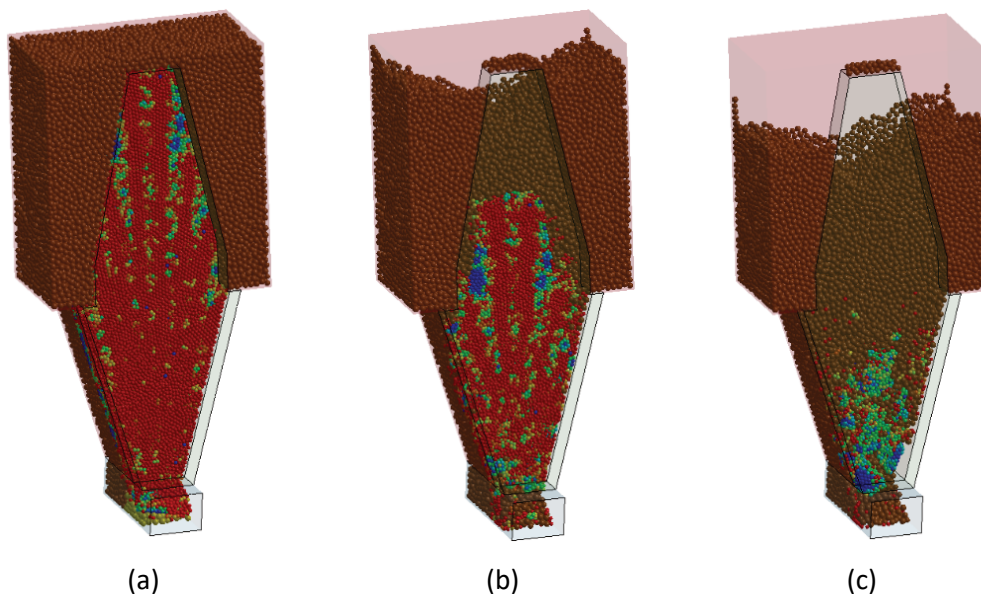


Figure 8 The flow out process of fragmented ore and waste rock, views from footwall. (a) Extraction = 5%; (b) Extraction = 21.5%; (c) Extraction = 87%

Figure 9 illustrates vertical displacement contours of the waste material at different ore extraction rates. The particles of ore fragments are hidden in Figure 9. The viewing direction is from the footwall. It shows that the displacement contours of waste are roughly elliptic, which agrees with Kvapil's original work (Kvapil 1998) that identified a central region of partial mass flow above the drawpoint surrounded by an ellipsoid of a draw. The elliptic flow is not clear in Figure 9c because the displacement range is too large and probably because of the contouring. Figure 9 shows that the displacement in Z-direction of waste at the upper portions is much smaller compared to the displacement of waste at the lower portions. However, the flow patterns do not match those measured in various marker experiments in full-scale SLC mines. The marker experiments showed that the extraction and movement zones were not a true ellipsoid (Brunton et al. 2010). One likely reason is that each fragment of waste is a single spherical particle in the numerical model. Another cause could be that the radius range of waste particles is 0.3–0.45 m. This means that the particle size difference is not significant.

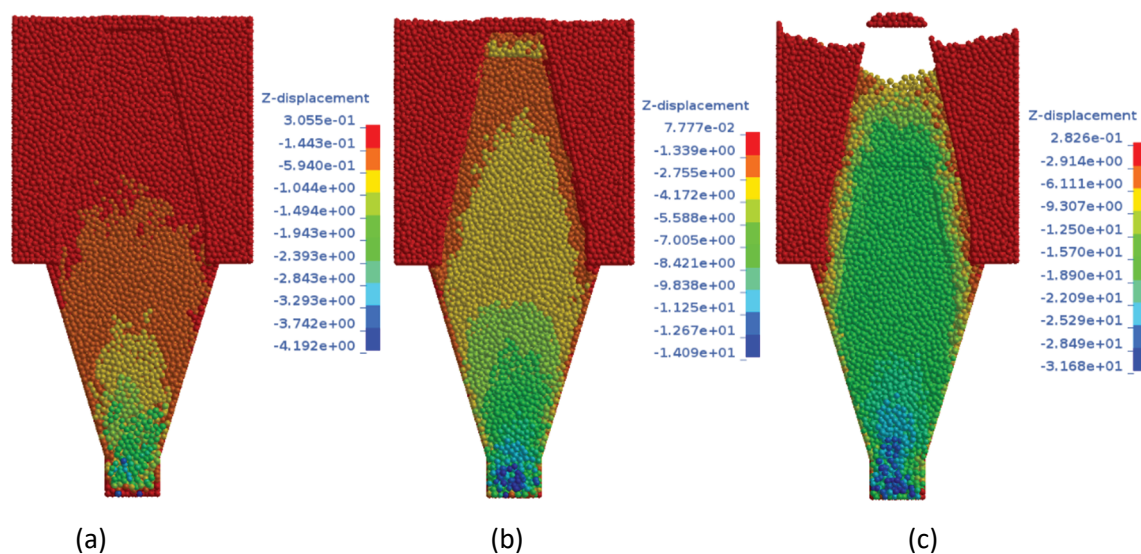


Figure 9 The displacement contours in Z-direction of waste (unit: m), views from footwall. (a) Extraction = 5%; (b) Extraction = 21.5%; (c) Extraction = 54.9%

The displacement contours in Z-direction of fragmented ore at different extraction rates are shown in Figure 10 and Figure 11 from different view angles. The particles of waste rock are hidden in Figure 10 and Figure 11 to facilitate the observation of the flow pattern of fragmented ore in different view angles.

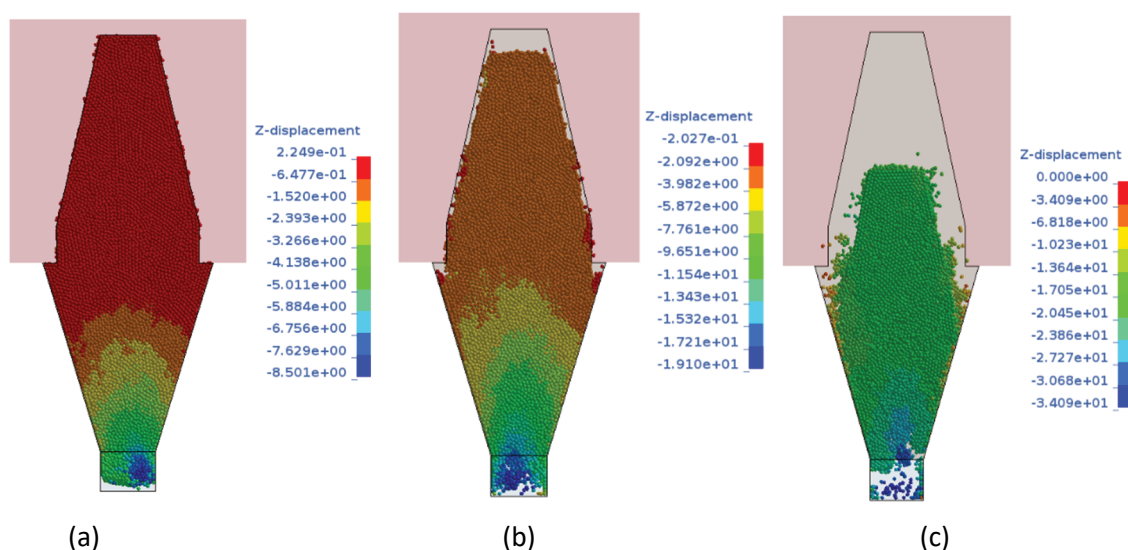


Figure 10 The displacement contours in Z-direction of fragmented ore (unit: m), views from footwall. (a) Extraction = 5%; (b) Extraction = 21.5%; (c) Extraction = 54.9%

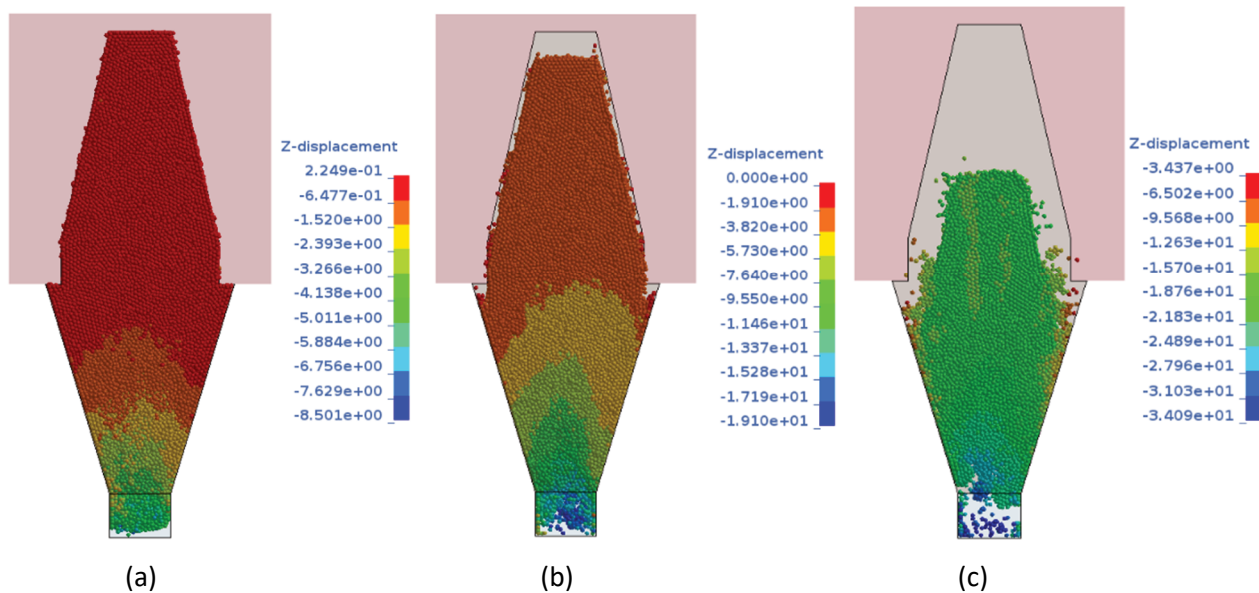


Figure 11 The displacement contours in Z-direction of fragmented ore (unit: m), views from hanging wall. (a) Extraction = 5%; (b) Extraction = 21.5%; (c) Extraction = 54.9%

The comparison of Figure 10 and Figure 11 shows that the displacement contour in Figure 10 is close to being elliptical while it deviates from an ellipse in the view from the hanging wall. This might happen because the visible fragments of ore in the viewing direction from the footwall are finer than those which are in the viewing direction from the hanging wall. The fine fragmentation makes the shape of fragments closer to a sphere, the fragment size uniform, and the flow process smooth, while the coarse fragmentation makes the shape of fragments irregular. Large fragment size and irregular shape could be the reasons that the gravity flow pattern of fragmented ore from the view of the hanging wall deviates from an ellipse.

3.3 Dilution analysis

As mentioned earlier, the major disadvantage of SLC is the relatively high dilution of the ore by waste. Dilution refers to the waste rock that is not separated from the ore during the operation and is mined with ore. This waste material is mixed with the ore in the mining process and sent to the mineral processing plant. Dilution increases the tonnage of ore while decreasing its grade, and can be defined as the ratio of the tonnage of waste mined to the total tonnage of ore and waste combined. It is commonly expressed in percent format as

$$\text{Dilution} = \frac{\text{Waste Tons}}{(\text{Ore Tons} + \text{Waste Tons})} \times 100\% \quad (1)$$

By calculating the remaining volumes of ore and waste in the model at different moments, the volumes of ore and waste that have been extracted can be obtained, and then the cumulative dilution at different moments can be calculated in terms of Equation 1. The cumulative dilution variation is shown in Figure 12. It shows that there is no dilution at the beginning, and then the cumulative dilution increases with the increasing extraction. The final dilution stays between 30% and 40%. Comparable results can be found in Selldén & Pierce (2004).

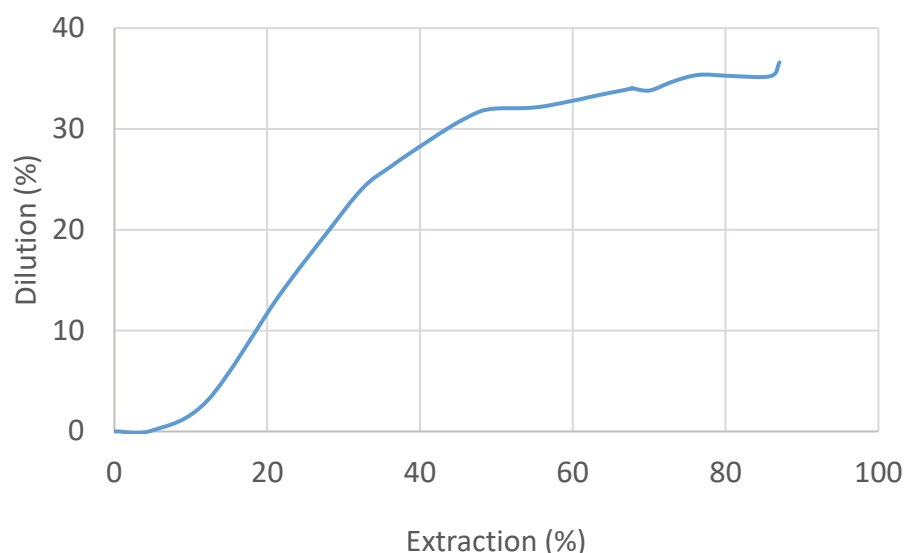


Figure 12 The relationship between dilution and extraction

4 Conclusion

Figuring out how the blast affects fragmentation and gravity flow in SLC mines is challenging. Efforts including full-scale and small-scale experiments and numerical modelling have been conducted to improve the understanding of this mining method. Earlier numerical modelling often focuses on either blasting fragmentation or gravity flow of ore. To further improve the understanding of SLC method and further improve the knowledge achieved in earlier studies, this paper presents a numerical method that can model both fragmentation by blasting and gravity flow of ore in one model with a single code.

The numerical results state that the presented model and method can give some observations that were detected in earlier experiments. For example, the fragments at the upper part of the ring are coarse while the fragments at the lower part of the ring are fine because of the specific charge distribution. The fragmentation becomes coarser with the increasing burden depth. The gravity flow modelling reveals that large fragments with irregular shapes could be the reason that the gravity flow pattern of fragmented ore deviates from an ellipse.

Moreover, the current modelling process has limitations. One is the model resolution. Low-resolution particles have been used because the discrete element model modelling is computationally expensive. The waste particles radius ranged between 0.3–0.45 m while the radius of ore particles is 0.24 m, which means the orebody to be blasted cannot be broken into particles with a radius below 0.24 m. A higher resolution is needed for further investigation. For the same reason, only one ring on one level is simulated and the model does not include the effects of blast preconditioning. Another shortcoming is that the joints in the rock mass are not included in the numerical model. Much research has showed that the joints in rock mass have a significant effect on rock fragmentation by blasting.

Acknowledgement

The authors acknowledge the strategic innovation programme Swedish Mining innovation (SMI) and LKAB Stiftelse. The Centre of Advanced Mining and Metallurgy (CAMM3) at the Luleå University of Technology, which is gratefully acknowledged, also supported the work.

References

- Brunton, I 2009, *The Impact of Blasting on Sublevel Caving Material Flow Behaviour and Recovery*, PhD thesis, University of Queensland, Brisbane.
- Brunton, ID & Chitombo, GP 2010, 'Modelling the impact of sublevel caving blast design and performance on material recovery', in JA Sanchidrián (ed.), *Proceedings of the 9th International Symposium on Rock Fragmentation by Blasting*, Granada, pp. 353–362.
- Brunton, ID, Fraser, SJ, Hodgkinson, JH & Stewart, PC 2010, 'Parameters influencing full scale sublevel caving material recovery at the Ridgeway gold mine', *International Journal of Rock Mechanics & Mining Sciences*, vol. 47, pp. 647–656.
- Campbell, AD & Power, GR 2017, 'Improving calibration of flow models against SLC marker trials by linking blasting effects to particle mobility', *Proceedings of the 13th AusIMM Underground Operators' Conference*, The Australasian Institute of Mining and Metallurgy, Melbourne, pp. 11–22.
- Campbell, AD 2018, 'Full-scale experiments to measure the effect of crosscut height on recovery in sublevel cave mines', in Y Potvin & J Jakubec (eds), *Caving 2018: Proceedings of the Fourth International Symposium on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 443–456.
- Castro, R, Gonzalez, F & Arancibia, E 2009, 'Development of a gravity flow numerical model for the evaluation of draw point spacing for block/panel caving', *Journal of the Southern African Institution of Mining and Metallurgy*, vol. 109, no. 7, pp. 393–400.
- DeGagne, D & McKinnon, S 2005, 'The influence of blasting fragmentation on ore recovery in sublevel cave mines', *Proceedings of the 40th U.S. Rock Mechanics Symposium*, American Rock Mechanics Association, Alexandria, pp. 1352–1361.
- DeGagne, D & McKinnon, S 2006, 'The influence of cave mass properties on discrete sublevel cave models', in *Proceedings of the 41st U.S. Rock Mechanics Symposium*, American Rock Mechanics Association, Alexandria, pp. 1997–2004.
- Furtney, J, Cundall, PA & Chitombo, G 2009, 'Developments in numerical modeling of blast induced rock fragmentation: Updates from the HSBM project', in JA Sanchidrián (ed.), *Proceedings of the 9th International Symposium on Rock Fragmentation by Blasting*, Granada.
- Hallquist, J 2016, 'LS-DYNA keyword user's manual', Livermore Software Technology Corporation, vol. 1 & 2.
- Itasca Consulting Group 2015, *PFC3D, Particle Flow Code in 3 Dimensions. Users Guide*, Itasca Consulting Group: Minneapolis.
- Karajan, N, Han, Z, Teng, H & Wang, J 2013, 'Interaction possibilities of bonded and loose particles in ls-dyna', 9th European LS-DYNA Conference. Manchester, UK.
- Kvapil, R 1998, 'The mechanics and design of sublevel caving systems', in RE Gertsch & RL Bullock (eds.), *Techniques in underground mining, Selections from underground mining methods handbook*. Littleton, USA: Society for Mining, Metallurgy, and Exploration, Inc.
- Lapcevic, V & Torbica, S 2017, 'Numerical Investigation of Caved Rock Mass Friction and Fragmentation Change Influence on Gravity Flow Formation in Sublevel Caving', *Minerals*, vol. 7, no. 4, p. 56.
- Newman, T 1996, 'Blasting of Intact Ore Against Caved Waste Rock at Kiruna', LKAB internal report, LKAB, Kiruna.
- Nordqvist, A & Wimmer, M 2016, 'Holistic approach to study gravity flow at the Kiruna Sublevel Caving mine', in *Proceedings of the Seventh International Conference & Exhibition on Mass Mining (MassMin 2016)*, The Australian Institute of Mining and Metallurgy, Melbourne, pp. 401–414.
- Petropoulos, N, Wimmer, M, Johansson, D & Nordlund, E 2018, 'Compaction of confining materials in pillar blast tests', *Rock Mechanics and Rock Engineering*, vol. 51, no. 6, pp. 1907–1919.
- Power, GR 2004, *Modelling Granular Flow in Caving Mines: Large Scale Physical Modelling and Full Scale Experiments*, PhD thesis, The University of Queensland, Brisbane.
- Selldén, H & Pierce, M 2004, 'PFC3D modelling of flow behavior in sublevel caving', in A Karzulovic & MA Alafaro (Eds.), in *Proceedings of the 4th International Conference and Exhibition on Mass Mining*, Santiago, pp. 201–214.
- Sharrock, G, Beck, D, Booth, G & Sandy, M 2004, 'Simulating gravity flow in sub-level caving with cellular automata', in A Karzulovic & MA Alafaro (Eds.), in *Proceedings of the 4th International Conference and Exhibition on Mass Mining, MassMin 2004*, Santiago, pp. 189–194.
- Šmilauer, V 2020, *Yade User's Manual*, <https://yade-dem.org/doc/user.html>
- Susaeta, A 2004, 'Theory of gravity flow (part 1)', in *Proceedings of the 4th International Conference and Exhibition on Mass Mining, MassMin 2004*, Santiago, pp 167–172.
- Teng, H & Wang, J 2014, 'Particle blast method (PBM) for the simulation of blast loading', in *Proceedings of the 13th International LS-DYNA Users Conference*, 7 p.
- Wimmer, M 2010, 'Gravity flow of broken rock in sublevel caving (SLC) – State-of-the art', Swebrec report 2010: P1, ISSN 1653–5006.
- Wimmer, M 2012, *Towards Understanding Breakage and Flow in Sublevel Caving (SLC) – Development of new measurement techniques and results from full-scale tests*. Doctoral thesis, Luleå University of Technology, Luleå.
- Wimmer, M, Nordqvist, A, Righetti, E, Petropoulos, N & Thurley, MJ 2015, 'Analysis of rock fragmentation and its effect on gravity flow at the Kiruna sublevel caving mine', *Proceedings of the 11th International Symposium on Rock Fragmentation By Blasting*, The Australasian Institute of Mining and Metallurgy, Melbourne, pp. 715–791.
- Yi, CP & Johansson, D 2014, 'Numerical comparison for blast-induced fragmentation of curved-hole and standard SLC rings', LKAB report.
- Yi, CP, Sjöberg, J & Johansson, D 2017, 'Numerical modelling for blast-induced fragmentation in sublevel caving mines', *Tunnelling and Underground Space Technology*, vol. 68, pp. 167–173.

