Numerical modelling approach for mine backfill

MUHAMMAD ZAKA EMAD

Department of Mining Engineering, University of Engineering and Technology, Lahore 54890, Pakistan
e-mail: muhammad.emad@mail.mcgill.ca

MS received 13 July 2015; revised 30 January 2017; accepted 5 February 2017; published 24 July 2017

Abstract. Numerical modelling is broadly used for assessing complex scenarios in underground mines, including mining sequence and blast-induced vibrations from production blasting. Sublevel stoping mining methods with delayed backfill are extensively used to exploit steeply dipping ore bodies by Canadian hard-rock metal mines. Mine backfill is an important constituent of mining process. Numerical modelling of mine backfill material needs special attention as the numerical model must behave realistically and in accordance with the site conditions. This paper discusses a numerical modelling strategy for modelling mine backfill material. The modelling strategy is studied using a case study mine from Canadian mining industry. In the end, results of numerical model parametric study are shown and discussed.

Keywords. Underground mining; backfill; sublevel stoping; FLAC3D; RS2.

1. Introduction

Canadian metal mines have adopted sublevel stoping method or one of its variations, such as blasthole stoping, vertical crater retreat (VCR) or vertical block mining (VBM) for the extraction of steeply dipping ore bodies [1]. In these methods, the ore body is divided into blocks or stopes, which are mined out while following a pyramidal mining sequence in transverse-retreat directions. In VBM, stope production is carried out in three or four blasts or lifts as shown in figure 1. Each lift is blasted and mucked before blasting the next one. Backfill is required to fill up the empty stopes once they are mined out. Cemented rockfill or consolidated rockfill (CRF) is a type of backfill made by mixing cement slurry with rock aggregates from either the development waste or quarry [2–4]. CRFs have a number of advantages over other backfill materials. Some of them include the ability of CRF to withstand higher exposure; CRF has higher stiffness, placement of CRF is simple, curing rate of CRF is fast, capital cost of CRF is low and required raw material for CRF is readily available [2, 5, 6]. When good practice is in place, CRF enables achieving good ground control by reducing footwall (FW) and hanging wall (HW) slough while mining adjacent stopes. It also provides a solid working surface for mining upper level ore blocks.

Stiffness and strength of CRF by and large govern its stability and a slight reduction in either may lead to failure of CRF itself. Factors like cementation, curing time, aggregate grading, aggregate shape, interlocking of aggregates, placement and mixing method and quality control dictate the strength and stiffness of CRF [3, 5–7]. Several authors have reported that blast vibrations of secondary stopes adjacent to

previously mined and filled primary stopes are amongst the major causes of destabilization of CRF, thus leading to dilution of precious ore [3, 6–10]. Yu [11] recommended that a safety factor of two is sufficient for CRF to withstand dynamic loading from blasting. In a study by Emad *et al* [10], the effects of different simulated blast loads have been examined through a numerical model parametric study. It has been shown that CRF failure could be initiated by blast vibrations. The current study presents a numerical modelling strategy for simulating mine backfill material. Numerical model construction can be accomplished using any of the commercial codes available like Rocscience's software RS2 (two-dimensional) and Itasca's finite-difference software FLAC3D (three-dimensional) with dynamic option [12]. Both programs are popular in the mining industry all over the world. It is a common perception that the backfill stability problem is three dimensional in nature and only three-dimensional software can represent a true picture of mining scenario. However, in this paper both RS2 and FLAC3D are used to present backfill modelling strategy.

2. Case study

The ore body at the case study mine is tabular and steeply dipping, and was mined by the open stoping mining method with delayed backfill. The ore is accessed by constructing mine shafts and drifts. The stopes are rectangular ore prism-shaped bodies in a mine plan, which are mined by blasting bottom up into three parts. The whole ore body is divided into primary and secondary transverse access stopes. Primary stopes comprise the virgin ore (undisturbed), and secondary stopes are the

Figure 1. Extraction sequence of stope in vertical block mining system. (a) Longitudinal section; (b) plan view.

stopes that are adjacent to the mined and backfilled stope. The sublevels are planned at a depth of every 30 m. The strike length of stope is 15 m with a width of 10 m. To analyse CRF stope for blast-induced vibrations, an isolated area of the mine was selected at a depth of 1100 m. Ore dilution was monitored by a cavity monitoring survey system (CMS) [10]. The CMS can compute stope over break in ore, HW, FW and backfill.

2.1 Mining process

The mining process starts with the stope preparation. This includes drilling a 1.2-m raise in a primary stope for developing a free face for blasting. In the next stage, long parallel drill holes are drilled from top access drift of primary stope. In case of a secondary stope, fan drilling pattern is used. The holes are charged with explosives and an initiation system followed by blasting of the stope into three parts. Firstly, the bottom most portion is blasted followed by mucking. Next in the sequence is the middle portion of the stope. Finally, the top portion, also termed as deck, is blasted and mucked away. The mucked ore is then placed in an ore pass that leads the ore to the ore bin and crusher, from where the ore is transported outside the mine. The stope is prepared for backfilling once all the three portions of the primary stope are blasted and mucked out. For stope preparation, 10–12 m³ of plain rock aggregates are placed in the stope. This may serve as a barricade for the backfill. Next, pre-mixed backfill known as cemented rockfill (CRF) is placed from the top drift of stope by a load-haul-dump machine. When the primary stope is backfilled, an adjacent stope termed as secondary stope is mined in a similar fashion, which is to blast and muck in three portions. Once the secondary stope is mined and mucked, it is filled with non-cemented backfill.

2.2 Backfilling

CRF backfill is prepared by mixing rock aggregate with binder slurry (blend of type-10 Portland cement and type-C

fly ash in 30:70). The rock aggregate used is graded on the surface and comes from a nearby quarry pit, and waste rock from the mine developments. The type of rock used for backfill is biotite-schist (with minerals biotite 16–24%, quartz 28–42% and feldspar 35–55%), which has low porosity with an average uniaxial compressive strength of 94 MPa and Young's modulus of 48 GPa. The rock is graded and passed through sieves to achieve 8" + 1¼" size range, and no fines are added. The rock aggregate is transported to the mine using trucks, which dump into a fill raise. The raise feeds several mine levels through finger raises. The aggregate level is maintained within 100 m from the surface to avoid impact damage due to free fall of aggregates. The estimated capacity of the fill raise is 9 t/ft. A 6" binder line connects an underground 20 t binder silo via main shaft. Binder is conveyed pneumatically through the binder line and compressors are used to provide turbulence to keep the binder suspended during the transfer. The water-to-binder ratio is generally kept at 0.50, maintained by the flash mixers located at main levels. The water used for binder preparation comes from a nearby lake. A flash mixer is used to produce the binder slurry, which is then pumped to stope. The slurry line is flushed after every shift to avoid line clogging. Once mined out, the stope is backfilled from the top sill drive using a load-haul-dump. The CRF mixing method is termed as the 'bucket method,' in which a bucket load of aggregate is showered by binder slurry right at the stope while it is still in the bucket. The load is then placed in the stope. The mine runs on two shifts per day and the current average placement rate of backfill is 500 t per shift. A stope that will not be exposed in future is filled with unconsolidated rockfill. The CRF, like all other cemented materials, acquires strength with time. In mining practice, CRF is allowed to cure from 3 days to 1 year, depending on the mine plan. After backfilling and curing a stope, the CRF column may be exposed to blast-induced vibrations from adjacent production stope. In this paper, the average of peak strength of CRF after 28 days is considered. The strength values are based on laboratory testing of backfill.

3. Numerical modelling strategy

Numerical modelling study of a backfill can be conducted using any of the commercial codes available like RS2 (two-dimensional) by Rocscience Inc. and FLAC3D (three-dimensional) with dynamic option by ITASCA [12]. Both programs are very popular in the mining industry all over the globe. The backfill stability problem is three dimensional in nature and only three-dimensional software can represent a true picture. However, in this work both RS2 and FLAC3D are used to show different backfill modelling approaches.

The primary and secondary stopes adjacent to each other should be constructed with a fine mesh for accuracy.

Table 1. Rock mass properties of geological units.

Material	σ_t (MPa)	E (Gpa)	ϕ (°)	c (MPa)	ν
Ore	0.80	82.65	45.80	13.12	0.12
Footwall	0.24	20.03	36.30	4.08	0.16
Hanging wall	0.23	11.15	37.20	2.67	0.25

Table 2. In situ stress tensor at a depth of 1100 m below the surface.

Stress tensor	σ_1	σ_2	σ_3
Magnitude [14] (MPa)	65.56	45.1	29.3
Orientation	Normal to ore body	Parallel to ore body	Vertical

However, rest of the mesh should be graded for a reduction in solving time. After setting boundary conditions and material properties, the model should be solved for equilibrium using a linear elastic constitutive model. The stope dimensions for this work are $15 \times 10 \times 30 \text{ m}^3$ in length, width and height, respectively. Rock mass properties for FW, HW, ore and CRF used for this work are shown in table 1. The rock mass properties are based on the actual laboratory testing of rock and backfill. The rock property values obtained from the laboratory are transformed to rock mass properties by incorporating discontinuities and joint data collected from the case study mine. The numerical model is initialized with two types of loading, which are the gravity and additional compressive stress to equate the in situ stress values at a depth of 1100 m below surface. table 2 shows the stress tensor values for the Canadian Shield. The in situ stress values were measured by Arjang [14].

The linear-elastic constitutive model may be employed to solve the model for approaching the initial condition. For an elastoplastic analysis the numerical model can be solved again while considering the model for a Mohr–Coulomb material. On reaching equilibrium the stope mining and backfilling sequence is followed. At this point, the numerical model is ready to receive the data on vibration acting on the free surface of the CRF face as input parameters. Based on the sensitivity analysis, model boundaries are placed at a minimum distance of 285 m from the stope, which corresponds to almost 10 times the maximum dimensions of stopes. In the FLAD3D model, the boundaries should be placed far away to absorb the excessive vibrations generated as a result of dynamic pulse to be applied at a later stage. CRF material is assumed to be homogeneous–isotropic for this research work. The two numerical models constructed with RS2 and FLAC3D are shown in figures 2 and 3, respectively.

Sensitivity analysis is required to determine the size of the model and size of the zone for accuracy of results. For mesh

Figure 2. Two-dimensional numerical model generated with RS2. (a) Numerical model; (b) primary and secondary stopes. **Figure 3.** FLAC3D model of CRF and adjacent production stope. (a) Prospective view; (b) stopes modelled with fine mesh.

sensitivity analysis the mesh is constructed with different mesh densities (8000–18,000 elements) in RS2 and (50,000–150,000 zones) in FLAC3D for this work. Mesh sensitivity analysis starts with mining a $15 \times 30 \text{ m}^2$ opening in RS2 and $15 \times 10 \times 30 \text{ m}^3$ opening in FLAC3D, and the model is solved for six different mesh densities one after the other. After solving each model the mesh displacements are observed at the centre of stope walls. The process is repeated until relatively consistent displacement values are obtained. The numerical model mesh selected for this analysis contains 13,112 elements in RS 2 and 125,430 zones in FLAC3D. Next a sensitivity analysis for model size is required for both static and dynamic analysis in FLAC3D. In this work it is achieved by varying the distance between regions under consideration and model boundaries. The sensitivity analysis for model boundaries is performed to diminish the effect of model boundaries during static and dynamic analysis. The final mesh used for this work is shown in figure 2 for RS2 and figure 3 for FLAC3D. As can be seen, both of the meshes are graded and the region under consideration comprises finer mesh for greater accuracy and for lower computation time.

3.1 Numerical modelling considerations for mine backfill

The two backfill models simulated with RS2 and FLAC3D comprise the primary stope, which will be mined out and backfilled at a later stage. There is a secondary stope right

Table 3. Material properties of materials modelled [13].

Material	σ_t (MPa)	E (Gpa)	ϕ (°)	c (MPa)	ν	GSI
Ore	1.860	101.24	47.2	21.62	0.10	76
Footwall	0.270	25.50	39.5	7.91	0.15	73
Hanging wall	0.790	12.66	40.0	4.14	0.21	80
Cemented rockfill [4]	0.030	2.50	37.0	1.10	0.35	–
Weak interface zones	0.001	0.25	20.0	0.10	0.50	–

GSI is the geological strength index of rocks, accounting for discontinuities and joints.

Figure 4. In-built interface elements in FLAC3D, modified after ITASCA [12].

next to a primary stope, which will be excavated after backfilling the primary stope. The backfill and rock interface is an important aspect when modelling backfill material (table 3) and it must be considered when simulating mine backfill. The interface can be simulated by generating either interface elements, a thin gap (5 cm) or weak zones (5 cm) in FLAC3D. In-built interface elements in FLAC3D are shown in figure 4. In case of RS2 software, a thin gap (5 cm), weaker zones, structural interface or built-in joints may serve as an interface between rock and CRF. In case no interface is simulated the code will consider backfill as a part of rock mass and thus results are affected. When setting up material properties in RS2 only body forces should

be considered for backfill material. The vertical stress transfer from top of the backfill is a common problem when simulating mine backfill material. This can be addressed by simulating a thin gap (1 m) on top of the backfill.

The numerical model boundary conditions are also very important when simulating backfill material. The conventional method of roller boundaries and initialization of stresses can be used with both FLAC3D and RS2. The boundary traction method proposed by Shnorhokian *et al* [15] is well suited to backfill modelling with FLAC3D. In the boundary traction method, model boundaries are set free while applying a nominal compressive stress load on model boundaries. The known value of in situ stresses at a location inside the model is computed and applied stresses are adjusted to attain the desired stress level. As indicated by Shnorhokian *et al* [15], the boundary traction method should be used for heterogeneous rock mass. This method has an embodied feature of calibrating the model when dealing with numerous geological units and geological structures. It has been found that the boundary traction method is not suitable for modelling backfill material with RS2. Backfill model can be simulated only with small strains; large strains cannot be modelled as the backfill material is plastic and deformed mesh cannot be solved.

3.2 Dynamic analysis

As discussed earlier, backfill is exposed to blast-induced vibrations from adjacent production stope. It is necessary to simulate the effects of blasting on backfill. The dynamic analysis is required to simulate blast loading effects and a fully dynamic analysis option is required. The dynamic analysis for mine backfill can be performed with FLAC3D software. To incorporate dynamic loading effects due to blasting in production stopes, model boundaries are transformed to viscous boundaries to help absorb any vibrations approaching the boundaries of model. Dynamic load reflected from model boundaries may lead to model failure in tension. Local damping value of up to 20% can be considered for assessing backfill. To apply the blast load on backfill stope, a blast wave form generated as a result of blast-induced vibration monitoring is applied or a dynamic pulse is applied as a stress history on the CRF stope. Blast wave data obtained from the on-site monitoring are very complex. It requires processing before interpreting and using it for numerical models. Generally, mining companies hire geophysics experts for interpretation of such data. The blast wave form can be utilized in a numerical model after conversion to Fish or Table function for FLAC3D. If the blast vibration data are not available, the blast load on the CRF–rock interface can be determined through the procedure of Sainoki and Mitri [16]. This includes studying the attenuation in rock and backfill, and calculating blast-induced load from blast design parameters. Blast pressure pulse components (x , y and z) are applied over a time period

Figure 5. Profile of the applied stress load on equivalent cavity [17].

Figure 6. Application of blast load on stope walls of the main backfill model. (a) Blast lift 1; (b) blast lift 2; (c) blast lift 3.

of almost 6 ms using the blast loading profile. The model is solved for 1 s, which is sufficient for analysing response of blasting events that are recorded in milliseconds. The profile of dynamic load can be represented as a decaying blast pulse (skew Gaussian curve), shown in figure 5 [17]. The blast load is applied on the walls of mined out stope as shown in figure 6. The applied load should be in accordance with the blasting sequence employed.

3.3 Failure condition

Several failure conditions have been considered by researchers to represent failure in backfill. The backfill material has been reported to fail with the development of relaxation zones or transformation of compressive stress into tensile stress in backfill. This is due to the fact that backfill is very weak in tension. Practically it has even lower tensile strength since the in situ strength of backfill varies a lot from the laboratory-determined values due to segregation, improper mixing and placement [3, 4, 7]. In this work, major principal stress contours and strength factor contours in backfill are used to define failure in backfill. The strength factor is defined as the ratio of strength to stress of the material. The development of tensile stress in backfill is considered as backfill failure. Similarly, a strength factor of less than 1 is considered as failure in backfill. Reportedly, backfill fails when there is tensile stress development, as backfill is weak in tension, and tensile stress development in backfill is considered as failure condition.

Figure 7. Contours of major principal stress in backfill.

Figure 8. Contours of strength factor.

4. Results and discussion

The numerical model is solved under static loading conditions in the first stage. This is followed by simulating the extraction sequence by extracting the primary stope and solving the model. The next step is to backfill the stope while creating the interface and solving the model. In the next step, the secondary stope is extracted and blast loads are applied in three portions as discussed earlier. The results of static loading on backfill are shown in figures 7, 8 and 9, respectively, for principal stresses, strength factor and lateral displacement. The strength factor is defined as the ratio of strength to stress, and a value of less than 1 defines failure. Figure 7 shows the contours of major principal stress in backfill from the RS2 software. As can be

Figure 9. Contours of lateral displacement.

Figure 10. Plot of vertical stress versus stope depth for different interfaces.

Figure 11. Plot of vertical stress versus stope depth while permitting vertical stress transfer.

Figure 12. Contours of major principal stress in backfill after static analysis.

Figure 13. Contours of strength factor for static analysis.

seen, the maximum stress in backfilled stope remains under 1 MPa while the minimum stress in backfill is 0 MPa for the major principal stress. There is no tensile stress development in backfill; hence, the backfill is stable under the given conditions.

The contours of strength factor in RS2 are shown in figure 8. The contours show that the backfilled stope appears to be stable under static loading conditions as the minimum value of strength factor in backfill is 1.58, which is greater than 1. The contours of lateral displacement in backfilled stope are shown in figure 9. As can be seen, there is little displacement in horizontal direction and the stope settles under gravity when exposed.

Vertical stress is computed at the centre of exposed face and plotted versus the stope depth to check the effect of

Figure 14. Contours of lateral displacement for static analysis.

different interface types; the results are shown in figure 10. As can be seen, different types of interface elements are simulated, including a thin gap, joint elements, structural interface, thin low strength zones and no interface. It is found that the most suitable way to simulate backfill and rock interface is with a thin gap. Backfill is simulated with no gap on top, thus allowing stress transfer vertically from the top, and a plot of vertical stress versus stope depth is shown in figure 11. As can be seen, a huge vertical stress of 2.5 is acquired at the top of backfill and 2.8 MPa is acquired at the bottom and by the backfill.

The same stope is modelled and assessed with FLAC3D software as discussed in section 3. The backfilled stope is subjected to gravity loads and blast loads in the later part. The results of static loading on backfilled stope are shown in figures 12, 13 and 14, respectively, for principal stress, strength factor and lateral displacements.

As can be seen, the results of FLAC3D are consistent with the ones produced by RS2. The stope appears to be stable as no tensile stress contours can be seen in backfill for both of the major principal stresses. Similarly, the strength factor value is 1.13, which suggests that the backfill is stable. The lateral displacement contours are shown in figure 14. The contours show that the backfill is settling under gravity loading. Figure 15 shows plots of vertical stress versus depth for various interface options in FLAC3D and figure 16 shows a plot of vertical stress versus stope depth when no gap is constructed on the top of backfill. Once again the results are identical to those from the 2D analysis conducted with RS2.

The static analysis is followed by dynamic analysis on CRF stope, which is carried out to simulate blast loading effects on CRF. Dynamic analysis is performed by transforming the model boundaries into viscous boundaries and applying a dynamic stress pulse on the model to achieve the monitored vibration levels in CRF. Once the model is

Figure 15. Plot of vertical stress versus stope depth for various interface options in FLAC3D.

Figure 16. Plotting vertical stress versus stope depth with no gap on top of backfill.

calibrated the model is completely solved for a dynamic time of 1 s, which is sufficient for simulating blast loading. The contours of major principal stress in CRF stope after extraction of secondary stope and application of blast loading are shown in figure 17. It can be seen that the minimum stress in backfill is tensile in nature and it is located at the topmost part of exposed backfill face. The maximum tensile stress is around 0.1 MPa. The value of tensile stress is very little compared with intact rock but it is too high for the backfill placed in underground mines. The location of failure in backfill is identical to the one shown by the CMS profiles reported in the literature [10, 18–21]. The contours of strength factor after dynamic analysis are shown in figure 18. As can be seen, the backfill is failing from the topmost part in wedge shape. This verifies the results shown in figure 17. The contours of lateral displacement are shown in figure 19 after the dynamic analysis of backfill. As can be seen, the maximum displacement is at the toe of the backfill, which is around 6 cm. This is not in line with the findings that backfill fails from the top.

Figure 17. Contours of major principal stress in backfill after dynamic analysis.

Figure 19. Contours of lateral displacement for dynamic analysis.

Figure 18. Contours of strength factor for dynamic analysis.

Figure 20. Principal stresses versus stope depth.

Major and minor principal stresses are computed at the vertical centreline of the exposed backfill face using FLAC3D. The plot of major and minor principal stress versus the stope depth is shown in figure 20. As can be seen, the maximum value of major principal stress approaches 0.6 MPa, while the minor principal stress approaches a maximum value of 0.1 MPa. Notably, a tensile stress zone (relaxation zone) can be seen on the top of backfill, which is an indication of backfill failure. Backfill failure has been reported at a similar location by a number of researchers [10, 18–21].

A history of vector sum of particle velocities is computed during the dynamic analysis, 2 m inside the backfill and rock interface at a depth of 2 m. The history plot is shown in figure 21 and it can be seen that a maximum magnitude

Figure 21. Particle velocity computed inside mine backfill.

Figure 22. Peak particle velocity versus stope depth.

of 347 mm/s is achieved after 0.007 s of application of blast load. The magnitude diminishes to the minimum value after 0.3 s.

The peak particle velocity is computed at the centreline of exposed backfill face and plotted against the stope depth in figure 22. As can be seen, the top region (0–10 m) of the backfill acquires higher peak particle velocity of more than 280 mm/s; notably, the same region is identified as the zone of relaxation.

5. Conclusions

A detailed numerical modelling strategy for mine backfill is shown using the commercial software packages. RS2 software produces promising results when it comes to the static modelling, but the results are on the conservative side. It is found that the rock–backfill interface is very important when modelling backfill material. A thin gap of 5 cm may serve as a better option for the interface. Similarly, it is found that a gap of 1 m on top of the backfilled material is essential for realistic results. With the interface simulated as a gap, the maximum stress in backfill is found to be 1 MPa. The strength factor is between 3.16 and 5.48, with the maximum lateral displacement of 6 mm at the toe. Results of the three-dimensional model showed that the backfill acquires a maximum stress of 1 MPa. The safety factor is between 1.4 and 10 with lateral displacement of 0.1 mm at the toe. The dynamic analysis conducted using FLAC3D shows very promising results in terms of predicting backfill failures. The major principal stress in backfill ranges from 0.09 MPa in tension to 0.6 MPa compression. The safety factor ranges from 0 to 1.1 with less than 0.9 in the topmost part. The lateral displacement is 7.3 cm at the toe of the backfill. The peak particle velocity of vibrations computed during the FLAC3D analysis is more than 375 mm/s. This is higher than the vibrations recorded in backfill in similar conditions.

References

- [1] Zhang Y and Mitri H S 2008 Elastoplastic stability analysis of mine haulage drift in the vicinity of mined stopes. *Int. J. Rock Mech. Min. Sci.* 45: 574–593
- [2] McKay D L and Duke J D 1989 Mining with backfill at Kidd Creek no. 2 mine. In: Hassani F P, Scoble M J and Yu T R (Eds.) *Minefill 89: Proceedings of the 4th International Symposium on Mining with Backfill.* Rotterdam/Brookfield, Montreal Canada: A A Balkema, pp. 161–172
- [3] Yu T R and Counter D B 1983 Backfill practice and technology at Kidd Creek Mines. *Can. Min. Metall. Bull.* 76: 56–65
- [4] Hassani F and Archibald J 1998 *Mine backfill.* Montreal, Canada: Canadian Institute of Mining, Metallurgy, and Petroleum
- [5] Kurakami T, Yamatomi J, Sato R, Sagawa Y and Murakami S 2008 Mining with backfill at the Hishikari Mine, Japan. *Gospod. Surowcami Min.* 24: 197–212
- [6] Yumlu M 2001 Backfill practices at Çayeli Mine. In: *Proceedings of the 17th International Mining Congress and Exhibition of Turkey, IMCET 2001*, pp. 333–340
- [7] Yu T R 1989 Some factors relating to the stability of consolidated rockfill at Kidd Creek. In: Hassani F, Scoble M J and Yu T R (Eds.) *Proceedings of the 4th International Symposium on Mining with Backfill.* Montreal, Canada: A A Balkema, pp. 279–286
- [8] Aitchison G D, Kurzeme M and Willoughb D R 1973 Geomechanics considerations in optimising the use of mine fill—part A: the investigation of the response of fill as a structural component. In: *Proceedings of the Jubilee Symposium on Mine Filling*, Mount Isa, The Australasian Institute of Mining and Metallurgy, North West Queensland Branch, Mount Isa, pp. 35–48
- [9] Doerner C A C 2005 *Effect of delayed backfill on open stope mining methods.* Mining Engineering, University of British Columbia, Vancouver, BC, Canada
- [10] Emad M Z, Mitri H and Henning J G 2012 Effect of blast vibrations on the stability of cemented rockfill. *Int. J. Min. Reclam. Environ.* 26: 233–243
- [11] Yu T R 1992 Mechanisms of fill failure and fill strength requirements. In: Kaiser P K and McCreath D R (Eds.) *Proceedings of the 16th Canadian Rock Mechanics Symposium*, Sudbury, ON, Canada, pp. 43–46
- [12] ITASCA 2009 Dynamic analysis. In: *FLAC3D—Fast Lagrangian Analysis of Continua in 3 Dimensions.* Itasca Consulting Group, Minneapolis, Minnesota, USA
- [13] Henning J G 1998 *Ground control strategies at Bousquet 2 Mine.* Department of Mining and Metallurgical Engineering, McGill University, Montreal, Canada
- [14] Arjang B 1988 *Premining ground stresses at the Bousquet/Dumagami mines, Cadillac, Quebec.* CANMET, Energy, Mines and Resources Canada, Div Report MRL 88-132 (TR)
- [15] Shnorhokian S, Mitri H S and Thibodeau D 2014 Numerical simulation of pre-mining stress field in a heterogeneous rockmass. *Int. J. Rock Mech. Min. Sci.* 66: 13–18
- [16] Sainoki A and Mitri H S 2014 Numerical simulation of rock mass vibrations induced by nearby production blast. *Can. Geotech. J.* 51: 1253–1262

- [17] van Gool B S 2007 *Effects of blasting on the stability of paste fill stopes at Cannington Mine*. School of Civil and Environmental Engineering, James Cook University, Australia, 2007
- [18] Emad M Z, Mitri H and Kelly C 2014 Effect of blast-induced vibrations on fill failure in vertical block mining with delayed backfill. *Can. Geotech. J.* 51: 975–983
- [19] Emad M Z, Mitri H and Kelly C 2014 State-of-the-art review of backfill practices for sublevel stoping system. *Int. J. Min. Reclam. Environ.* 29: 544–556
- [20] Chen D, Messurier M L and Mitchell B 2004 Application of cemented aggregate fill at Barrick's Darlot Gold Mine. In: Aimin Z (Ed.) *Minefill 2004: Proceedings of the 8th International Symposium on Mining with Backfill*, The Nonferrous Metal Society of China, Beijing, China, pp. 82–89
- [21] Ran J and Watunga T 2012 Application of consolidated rockfill to open stoping in underground mines. In: Hawkes C (Ed.) *Proceedings of RockEng12—Rock Engineering for Natural Resources*, Canadian Institute of Mining and Metallurgy, Edmonton, AB, Canada, pp. 197–207