Unplanned ore dilution control in longhole mining using sill pillars – A case study

Tuo Chen, Hani S. Mitri
McGill University, Montreal, Canada

ABSTRACT: This paper discusses the main causes for unplanned ore dilution in longhole mining and possible mitigation measures. It reports on the results of a case study of an underground mine that uses the longitudinal retreat method for the extraction of a narrow gold-silver orebody. The study is conducted with finite difference software FLAC3D. The modelling technique tracks and fills the cavities created by progressive overbreak with cemented rockfill in bottom-up sequence. In this work, a strategic measure of ore dilution control is explored by incorporating a sill pillar in the mine plan. Comparison of two mine plans - with and without sill pillar - reveals the benefits of sill pillar on unplanned ore dilution control, especially in the three mining levels immediately above the sill pillar. The findings of this work could be equally applicable to similar mining systems with one or more sill pillars in each mine plan.

Keywords: Underground mining, sill pillar, unplanned ore dilution, numerical modelling.

1 INTRODUCTION

Longhole mining is a popular method for the extraction of steeply dipping ore deposits. In this method, the orebody is divided into sublevels and each sublevel is further divided into stopes. The method, also known as sublevel stoping, is widely practiced in Canadian mines due to its inherent safety and efficiency. Narrow and tabular orebodies are usually mined with longitudinal retreat along the orebody strike whereas wider deposits are extracted with transverse stoping along the orebody thickness in a primary-secondary stope sequence (Henning & Mitri 2007). Stopes are drilled and blasted from an overcut, and blasted ore is mucked from an undercut access. Production drilling patterns may vary depending on the thickness of the orebody. For narrow veins, a ring of two or three holes is adopted whereas in tabular orebodies, a fan pattern is employed. Drilling rings are repeated along the stope strike with a specified burden. Backfilling is used in different forms depending on the selected type. The most common types of backfill are paste-fill, cemented rockfill, sandfill, and uncemented rockfill. The latter is simply waste rock. The choice of backfill material and system depends on the selected mining method, stope sequencing, availability of raw materials, and capital and operating cost of the backfill system. More information about backfill practices in sublevel stoping systems is found elsewhere (Emad et al. 2015). Despite their popularity, longhole mining methods are notorious for unplanned ore dilution, i.e., the failure or overbreak of the stope walls into the stope cavity during production blasting. This is due to the nature of the method which creates non-entry stopes making it difficult to support the stope walls, unlike methods like cut-and-fill where the stope walls can be directly accessed and reinforced from the cut. Unplanned ore dilution can have a significant negative impact on the economics of a mining operation as the overbreak material is either of low economic value (below the cut-off grade) or even waste rock. Therefore, the subject of ore dilution in longhole mining has attracted the attention of many researchers over the last 30 years. Past research has identified the main factors influencing the occurrence of overbreak in longhole stopes. These are discussed below.

2 CAUSES AND CONTROL OF UNPLANNED ORE DILUTION

Ore dilution can be caused by one of several factors such as stope dimensions and its construction setting, stope type, host rock mass quality, proximity to geological structures, mining depth, in-situ stress orientation with respect to stope, drill hole deviation, and blast-induced vibrations. Henning & Mitri (2008) examined a comprehensive database of stope cavity surveys of 172 sequentially mined long hole stopes. They reported that, in addition to stope dimensions, the amount of unplanned dilution differed according to stope type with secondary stopes generating a greater volume of hanging-wall dilution than primary stopes. Mitri et al. (2010) showed the benefits of reduced stope strike length and stope height through surveyed stope profile data and numerical modelling. Stope height was found by far to be one of the most critical design parameters for unplanned dilution that must be given careful consideration in mine design studies. Stope undercutting is another key parameter that produces more overbreak than stopes with no undercut (Wang 2004 and Mitri et al. 2010). Emad et al. (2014) used 3D dynamic modelling to examine the effect of blast-induced vibrations in a secondary stope production on the exposed backfill face of a previously mined primary stope. A comparison with surveyed cavity profiles demonstrated that blast-induced vibrations can be a primary cause for wedge-type failure of the exposed backfill face into the stope cavity. The abovementioned factors can be grouped into two categories namely controllable and uncontrollable or natural factors, whereby controllable parameters are essentially those associated with stope design, construction setting, blasting, and backfill.

A few tactical measures have been suggested to help mitigate the severity of stope wall overbreak in longhole mining and reduce unplanned ore dilution. Urli & Esmaieli (2016) examined the merits of leaving an ore skin in the stope to support the overlying hanging wall using discrete element modelling. Such a tactic would inherently prevent ore dilution from taking place albeit at the expense of leaving some ore unmined. Henning & Mitri (2008) reported on the practice of stope hanging wall support with cablebolts at Bousquet Mine in Quebec. In one mining zone, upward fans of cablebolts are installed into the hanging wall from every stope access to help minimize the unravelling of the hanging wall rockmass. In another mining zone, a drift is driven in the hanging wall parallel to the stope strike, from which a fan down and a fan up of cablebolts are installed towards the stope hanging walls. The fan down cablebolt support proved more efficient in secondary stopes.

3 CASE STUDY MINE

From a mine planning point of view, sill pillars are used to divide the orebody into mining zones to allow stoping activities to take place simultaneously in more than one zone thus increasing the daily production rate. Chen & Mitri (2021) investigated the potential merits of strategically placing the sill pillars to minimize unplanned ore dilution in a feasibility study of a shallow, narrow vein gold-silver deposit owned by Kinross Gold Corporation in Canada. The deposit is underlain by a bimodal suite of andesite fragmentals, feldspar-hornblende porphyry, and andesite (trachytic andesite) flows consisting of minor basalt that dips shallowly eastward. Mineralization is hosted by colloform to crustiform-banded quartz-adularia and polyphase breccias. The 4 m wide vein deposit is found approximately 45 m below the undulating ground surface; it is 230 m deep and 550 m long striking in the SE direction with an average dip of 75° to the SW direction. Figure 1 illustrates a longitudinal section of the projected mine plan and Table 1 lists the elastic properties – modulus of elasticity E_{rm} and Poisson's ratio ν of the rockmass, the Hoek-Brown criterion strength parameters (m_i, m_b, s, UCS) (Hoek et al. 2002) and the tensile strength σ_t of the ore and host rock materials. Horizontal-to-vertical stress ratios are estimated to be 1.5 and 1.8 in the x- (orebody strike) and y-directions, respectively, with the vertical stress being estimated by the gravity pressure of ρgh where h is the depth below the ground surface.

Table 1. Geomechanical properties of the ore and host rock.

Material	$E_{rm}(GPa)$	ν	$\rho\ (g/cm^3)$	m_i	m_b	s	$UCS(MPa)$	$\sigma_t(MPa)$
Host rock	18	0.25	2.42	19	4.2	0.009	50	0.23
Ore	8	0.25	2.48	20	3.1	0.003	90	0.22

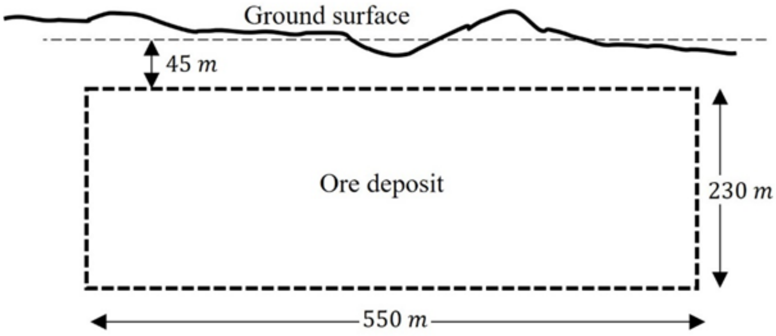


Figure 1. Longitudinal section of the case-study ore deposit.

The feasibility study by Chen & Mitri (2021) employed the Avoca method, which uses waste rock as the backfill material. Unplanned ore dilution is estimated based on the Equivalent Linear Overbreak Slough (ELOS) suggested by Clark & Pakalnis (1997) as

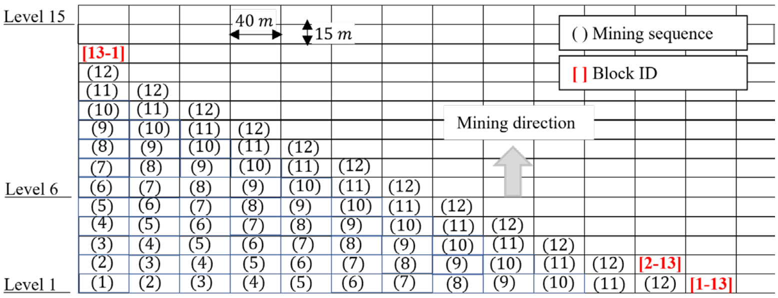
$$ELOS = \frac{Volume\ of\ slough}{Stope\ wall\ surface\ area} \tag{1}$$

A FLAC3D model was developed to simulate the extraction of the orebody (Figure 1) with the Avoca method by dividing the orebody in to 15 levels – numbered 1 to 15 – at 15 m intervals. A sill pillar is placed at different elevations and the results are examined in terms of ELOS. More specifically, the sill pillar was placed on level 5, 6, 7 and 8 to examine its impact on hanging wall overbreak. Sill pillar thickness is assumed equal to that of a level interval. The results show that all sill pillar simulations showed smaller ELOS than the case of mining all 15 levels without the use of a sill pillar. The placement of the sill pillar at approximately one third of the orebody height (level 5 or 6) showed the best results in terms of dilution. The largest ore dilution reduction from the base case is found to be in the stope immediately above the sill pillar. For example, for a sill pillar on level 6, the overbreak in level 7 is 73% less than that without a sill pillar. Overall, the mean reduction in ELOS is 32% for sill pillar placement on level 5 or 6.

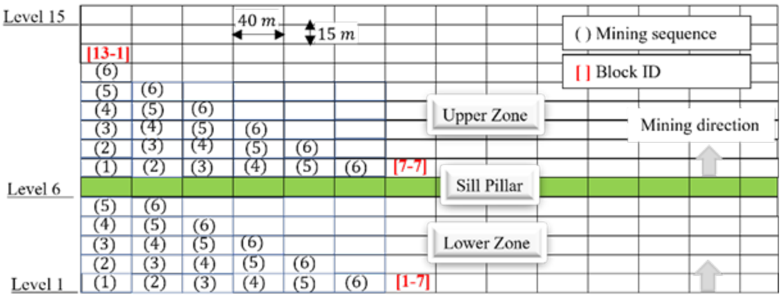
4 NUMERICAL MODELLING

The current study is an extension of the work being done on the feasibility study. It uses the method of longitudinal retreat with delayed backfilling with cemented rockfill (CRF). While the mining cycle of this method is slower than that of the Avoca method, it was successfully used at Lapa Mine owned by Agnico Eagle Mines Ltd to reduce ore dilution caused by strong foliation at the orebody contacts (Goodfellow et al. 2009). The CRF is deemed suitable as it is stronger than paste fill. It offers immediate support to the stope walls resulting in better dilution control. Thus, the goal of this study is to establish if sill pillar placement is still warranted in a system that employs stronger and more immediate backfill support. Figure 2 illustrates the two mine plans for FLAC3D modelling. Stopes are 15 m high and 20 m long. Every pair of stopes is combined for modelling purposes resulting in a 40 m block. Based on the results from Chen & Mitri (2021), only the case of sill pillar on level 6, which gave optimal results, will be analyzed, and compared with the baseline case of no sill pillar (Fig. 2a). The system with a sill pillar (shown in Fig. 2b) enables mining simultaneously in two zones – marked upper zone and lower zone – in a bottom-up sequence. Twelve and six mining stages are modeled for the systems without and with sill pillar, respectively, and ELOS results are recorded. The elastic CRF properties are assumed as follows E=2.5 GPa, and ν=0.2.

Figure 3 shows the layout of the mine wide FLAC3D model. It is 1000 m long, 500 m wide, and 550 m deep. All boundaries are constrained with rollers except for the top boundary (ground surface). Once the model is initiated with the in-situ stress condition, mining and filling stages are simulated per the proposed sequence shown in Figures 2a and 2b. Overbreak is considered to occur when yielding is predicted. Yielding zones in the stope walls are tracked and replaced with backfill material prior to mining the next stope in the sequence. This technique was deemed more conservative for the estimation of unplanned ore dilution (Mitri & Chen 2021).



(a) Mining system without sill pillar



(b) Proposed mining system with a sill pillar

Figure 2. Two mining systems for FLAC3D modelling.

Table 2. Comparison of ELOS results on level 7.

Block ID	7-1	7-2	7-3	7-4	7-5	7-6
Without sill pillar	3.9	4.9	5.2	5.3	5.3	5.4
With sill pillar	1.9	2.1	2.2	2.2	2.2	2.2

The effect of the sill pillar on lower zone dilution is not apparent as both mining systems modelled (Figure 2) employ identical stope extraction sequence in the lower zone. The benefits of the sill pillar are pronounced in the levels overlying the sill pillar, i.e., as of level 7. This is evident from the ELOS results in Table 2 for level 7. Figure 4 displays stope yielding in Block [7-4]. It shows much greater yielding for the pillarless system. Figure 5 compares the σ_3 principal stresses around Block [7-4]. The sill pillar system shows lower hanging wall tensile stress 0.1 MPa vs 0.5 MPa for the pillarless system). Table 3 summarizes the ELOS results for both mining systems for the extraction sequence shown in Figure 2. Overall, with a sill pillar placed at level 6, the average hanging wall ELOS values drop by 58%, 20.8% and 6.8% at levels 7, 8, and 9, respectively from the pillarless system.

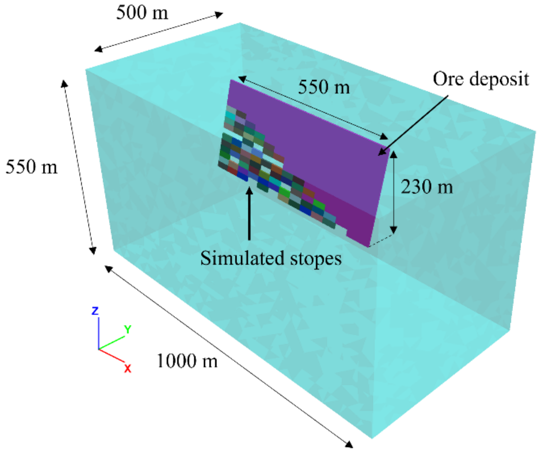
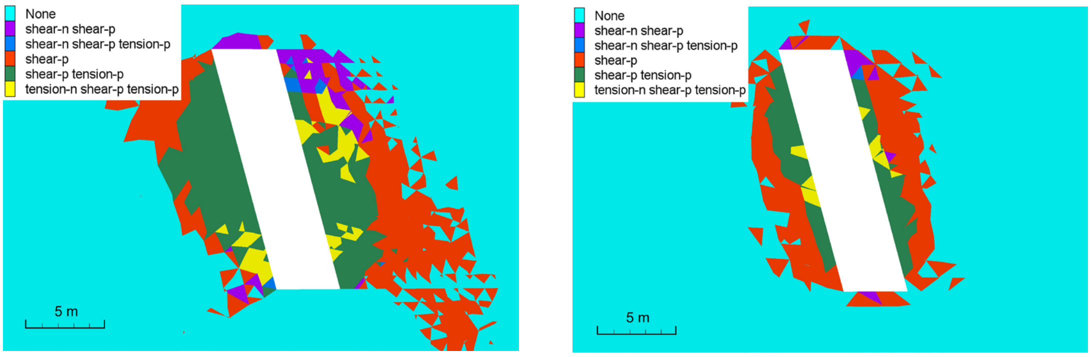
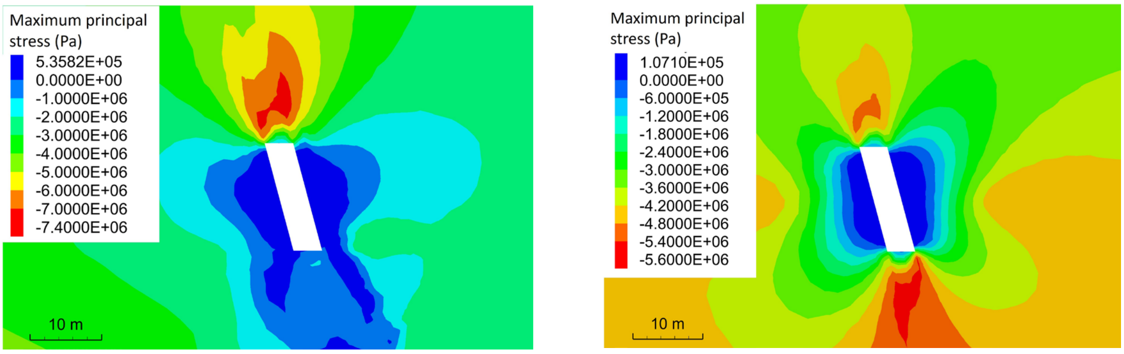


Figure 3. Isometric view of FLAC3D model.



a) Without sill pillar b) With sill pillar

Figure 4. Yield zone distribution around Block [7-4].



a) Without sill pillar b) With sill pillar

Figure 5. Confinement (σ_3) stress distribution around block [7-4].

Table 3. ELOS results in meters for two mining systems with and without sill pillar.

Block	Without pillar	With pillar
1-1	2.4	2.4
1-2	2.6	2.6
1-3	2.7	2.7
1-4	2.6	2.6
7-1	3.9	1.9
7-2	4.9	2.1
7-3	5.2	2.2
7-4	5.3	2.2

1-5	2.6	2.6
1-6	2.6	2.6
2-1	3.8	3.7
2-2	4.7	4.8
2-3	4.8	4.8
2-4	4.8	4.8
2-5	5.1	5.1
3-1	4.1	4.1
3-2	5.2	5.3
3-3	5.5	5.5
3-4	5.4	5.5
4-1	4.3	4.3
4-2	5.4	5.5
4-3	5.5	5.7
5-1	4.1	4.3
5-2	5.4	6.1
7-5	5.3	2.2
7-6	5.4	2.2
8-1	3.6	2.9
8-2	4.8	3.9
8-3	5.0	3.9
8-4	5.2	4.1
8-5	5.2	4.1
9-1	3.3	3.2
9-2	4.7	4.3
9-3	5.0	4.5
9-4	4.7	4.6
10-1	3.1	3.1
10-3	4.6	4.4
10-3	4.6	4.4
11-1	2.9	2.9
11-2	4.1	4.1

5 CONCLUSION

Unplanned ore dilution has a direct influence on the profitability of a mining operation. In this work, a strategic measure of ore dilution control in longhole mining is explored by incorporating a sill pillar in the mine plan. It is shown that a sill pillar placed on level 6 of 15 produces 13.6% less unplanned ore dilution than a mine plan without a sill pillar. Less hanging wall overbreak could be achieved if more sill pillars are employed in the mining plan. The results are promising, especially that sill pillar recovery is possible for cemented backfill systems. Sill pillar recovery is a well-established practice in Canadian mines and is usually done at the end of the mine plan. The findings of this work could be equally applicable to other mining systems of similar characteristics.

REFERENCES

Chen, T. & Mitri, H.S. 2021. *Strategic sill pillar design for reduced hanging wall overbreak in longhole mining*. International Journal of Mining Science and Technology 31 (2021) 975–982.

Clark, L. & Pakalnis, R. 1997. *An empirical design approach for estimating unplanned dilution from open stope hanging walls and footwalls*. In: Proceedings of the 99th Annual General Meeting, CIM AGM. Vancouver, BC Canadian Institute of Mining, Metallurgy and Petroleum

Emad, M.Z., Mitri, H. & Kelly, C. 2015. *State-of-the-art review of backfill practices for sublevel stoping system*. International Journal of Mining, Reclamation and Environment, 29 (6), 544-556

Emad M.Z., Mitri H. & Kelly, C. 2014. *Effect of blast-induced vibrations on fill failure in vertical block mining with delayed backfill*. Can Geotech J. 51(9):975–983.

Goodfellow R., Mitri, H.S., Bedard, N. & Lecomte, E. 2009. *3-Dimensional numerical modelling of stope sequencing for mine planning*. In: Proc 43rd US Rock Mechanics Symposium.

Henning, J.G. & Mitri, H.S. 2007. *Numerical modelling of ore dilution in blasthole stoping*. Int J Rock Mech Min Sci. 44(5):692–703.

Henning, J.G. & Mitri, H.S. 2008. *Assessment and Control of Ore Dilution in Long Hole Mining: Case Studies*. Geotech Geol Eng (2008) 26:349–366

Hoek E., Carranza-Torres, C.T. & Corkum, B. 2002. *Hoek-Brown failure criterion - 2002 edition*. In: Proc 5th North American Rock Mechanics Symposium, Toronto, 7-10 July 2002, 267- 273.

Mitri, H.S., Hughes. R. & Lecomte, E. 2010. *Factors influencing unplanned ore dilution in narrow vein longitudinal mining*. In: Proc. SME Annual Meeting and Exhibit. pp. 448–454. ISBN: 978-1-61738-082-2

Urli V. & Esmaieli, K. 2016. A stability-economic model for an open stope to prevent dilution using the ore-skin design. Int J Rock Mech Min Sci. 82:71–82.

Wang, J. 2004. *Influence of stress, undercutting, blasting and time on open stope stability and dilution*. PhD thesis. University of Saskatchewan.