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ON THE MERITS OF MODIFIED SUBLEVEL CAVING MINING METHOD – A CASE STUDY

Sublevel caving (SLC) mining method has several features that make it one of the preferred methods for ore extraction due to its high productivity and early access to ore recovery. However, there are some major challenges associated with the SLC method such as ground surface subsidence, high unplanned ore dilution, and the potential for air blast. To remedy these shortcomings, a recent approach has been to modify the SLC method by introducing rockfill into the void atop the production zone to provide continued support for the host rock and prevent it from caving. This paper discusses in detail the merits of the Modified SLC or MSLC. In comparison with other long-hole stoping methods that are predominantly practiced in metal mines, the MSLC method boasts several advantages. Early production achieved from the topmost level helps reduce the payback period. Productivity is enhanced due to multilevel mining without the use of sill pillars. The cost of backfilling is significantly reduced as there is no need for the construction of costly backfill plants. Continuous stoping is achieved without delays as mining and backfilling take place concurrently from separate mining horizons. A significant reduction in underground development costs is achieved as fewer slot raises and crosscuts are required for stope preparation. These merits of the Modified SLC method in steeply dipping orebodies are discussed by way of reference to real-life mine case studies. Dilution issues are addressed, and the benefits of top-down mining are explained. Typical mine design, ventilation, materials handling, and mining schedules are presented. Geomechanics issues associated with different in-situ stress environments are discussed and illustrated with simplified mine-wide 3D numerical modeling study.

Keywords: Underground mining; Long hole mining; Sublevel caving; Modified sublevel caving; Surface subsidence; Ore dilution; Backfill; Air blast; Mine design; Numerical modeling

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1. Introduction

In the wake of rising energy and mining costs, environmental considerations, and the depletion of high-grade and near-surface orebodies, mining companies are compelled to find innovative ways to operate profitably and remain environmentally friendly. Many recently discovered metal orebodies are tabular, low grade, and are found in geological conditions that are too complex to mine profitably using traditional mining methods. Thus, alternative mining methods must be sought [1]. One of the advanced and innovative techniques for mining steeply dipping tabular and wide orebodies with weak hanging walls but fairly competent footwall conditions that require minimal ground support is the Sublevel Caving (SLC) mining method. This is due to its low cost, high efficiency, early access to ore recovery, operational safety, multi-level mining, high mechanization, and flexibility [1-3].

Thus, the SLC mining method has become popular in many underground mines. The method involves drawing ore from drifts surrounded by waste rock that caves under mining-induced stresses and gravity, filling the void created by the extracted ore. Typically, the blasted ore directly contacts the caved rocks during extraction [4].

The earlier application of the SLC mining method was in very weak grounds, both ore and host rock, where smaller headings were developed and supported with timber sets. Mechanization was thus not feasible. More recently, the SLC mining method has been applied to stronger orebodies, allowing larger openings to be developed. Consequently, this has led to a high level of mechanization. However, the method still relies on the caving of the walls and therefore requires the host rock to be weak. This situation leads to four major challenges that impact the environment, profitability, and safety of the SLC mining operation. These challenges include air blast and dilution as demonstrated in Fig. 1. Other reported challenges are surface subsidence and inrush as will be discussed below.

1.1. Surface Subsidence

The SLC mining method causes significant strata movement and subsidence ranging from a few millimeters to several meters by caving the surrounding rock into the mined-out area, presenting substantial risks to human lives and ground surface infrastructure [5-8]. Surface subsidence impacts the location of surface infrastructure for the mining operation. No meaningful infrastructure should be constructed within or near the anticipated subsidence zone. This could entail an increase in capital and operational expenditure of the mining operation. Another drawback of surface subsidence pertains to its ecological ramifications, impacting both topsoil degradation/removal and subsurface hydrogeology. One of the primary reasons for adopting an underground mining method is to preserve the ground surface ecology for environmental protection. The occurrence of surface subsidence because of underground mining defeats this objective.

While several researchers [9-11] focused their studies on predicting, monitoring, and assessing the failure mechanisms of surface subsidence through GPS monitoring, numerical simulation, and empirical analyses, others aimed to investigate and evaluate the impacts of subsidence resulting from caving mining methods. Parmar et al. [12] evaluated the effect of subsidence on surface infrastructure at the Anomaly No. 12 Sechahun iron deposit mine in central Iran. The results indicated that surface infrastructure located within the subsidence zone had to be moved 2-3 km away from the orebody center. A quantitative assessment of the impact of surface subsidence on the environment in the Hongqi mining area was conducted by Jianjun et al. [13]. They reported that a subsidence area of about 3.4 km^2 necessitated the relocation of 1524 houses. The loss of ecosystem services and the relocation exercise due to subsidence amounted to over $2 million. Li et al., 2019 argued that a mine can experience huge economic losses because of surface subsidence caused by caving mining methods.

1.2. Dilution

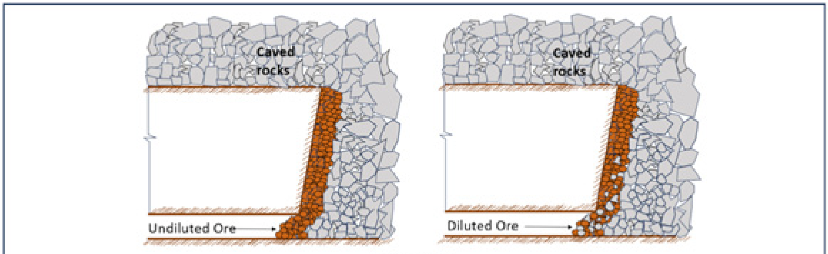
Ore dilution, as shown in Fig. 1a, is one of the biggest challenges encountered in SLC mining operations. This is typically caused by the direct contact between blasted ore and caved (waste) rocks [4]. Although dilution cannot be entirely eliminated from a mining operation, the success of the SLC mining method is largely influenced by the level of acceptable dilution budgeted for the extraction process as it is critical to the overall economics of the mine. Dilution levels that are considered acceptable can vary greatly depending on cut-off grade and the mining method adopted [14]. However, based on the Canadian experience, ore dilution exceeding 20% is generally considered to be excessive [15].

While much work has been dedicated to controlling dilution in underground mines in general, e.g., [16], some researchers have suggested specialized solutions, particularly for the SLC mining method. Tao et al. [4] proposed a new diversion drawing technique to control dilution by changing the flow path and velocity of caved ore and host rock using triangular ore columns known as diversion blocks. A steel-concrete structure artificial roof was also proposed by Shao [17] which achieved certain results when applied in the Gongchangling mine. Other researchers focused on minimizing dilution by proposing several concepts of ore fragment isolation which was first proposed by Malakhov [18].

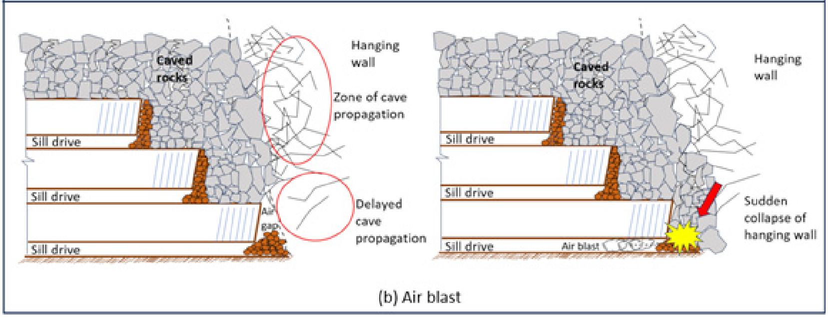
1.3. Air Blast

Air blast is a sudden movement of a compressed air mass through an underground opening due to a collapse or slide of a large volume rock mass of the host rock into an air-filled void [19]. As one of its main features, the SLC mining method relies on the caving of the walls to fill the void created atop the mining zone following the extraction of ore. However, in some situations, either the walls are not weak enough to cave or the stresses acting on the walls are not high enough to induce sliding, thereby delaying cave propagation. This could lead to the creation of a large air-filled void in the caved zone owing to the constant drawing of ore material in relation to the rate of cave propagation [20]. Suddenly and unexpectedly, the walls collapse into the air-filled void, compressing the air mass beneath it and forcing it out through adjacent openings causing air blast as shown in Fig. 1b. This phenomenon could cause injury to mine personnel, damage to equipment, or disrupt mine operations [19].

The consequences of air blasts in underground mines can be devastating. In Zimbabwe, Epoch mine reported considerable damage to the shaft system due to an air blast incident that occurred in 1978 [21]. Northparkes Mines in New South Wales, Australia reported fatalities due to an air blast that took place On November 24, 1999 [19]. The Codelco Chile Salvador Division suffered from an air blast incident caused by sudden rock mass failure spanning an area of approximately 15,000 m^2 above an air-filled void [22]. Given the increasing number of caving operations, air blast is likely to become an increasing phenomenon.



(a) Dilution



(b) Air blast

Fig. 1. Dilution and Air Blast Challenges of Sublevel Caving Mining Method

1.4. Inrush

Another major challenge faced by the SLC mining method is inrush. An inrush is basically a high-volume water inflow that could be accompanied by mud [23]. Water inflows are water gushes from the SLC draw-points due to water accumulation in the caved zone over time. Since the underground workings in the SLC method are connected to the ground surface, rainfall or snow melt as well as nearby lakes or streams could find their way to the SLC draw-points through the caved rocks. Excessive inrushes may lead to fatality, equipment damage, dilution, production delays, and possibly mine closure [24]. A good hydrogeological model for the caving system and the implementation of a robust water management system are key to avoiding or reducing the stringent impact of inrushes on any caving operation. Based on literature, the solutions suggested to deal with all the challenges of inrush appear to be more mitigative than preventive, e.g., [25]. This paper discusses in detail the Modified Sublevel Caving (MSLC) mining method and shows how it inherently eradicates the challenges of dilution, air blast, and inrush, yet benefits from all the advantages of the traditional SLC mining method.

2. Modified Sublevel Caving (MSLC) Mining Method

The MSLC mining method has the same characteristics as the traditional SLC mining method except that the orebody and host rock do not necessarily have to be weak since no caving of the host rock is required in this method. This is because a deliberate attempt is made to backfill the void with waste rock through a fill raise created atop the mining zone to support the host rock walls. To secure the underground mine workings, a crown pillar is required to separate the underground mine from the surface environment. To support the walls and prevent caving, the MSLC method introduces uncemented rockfill into the void from the topmost level (backfill drift). The rate of backfilling the void below from the topmost level corresponds to the rate of drawing ore material from the lower levels. This way, the void is always filled with waste rock with no significant air gaps, thus preventing the host rock walls from collapsing and avoiding the possibility of both surface subsidence and air blast.

2.1. Mining System

Typically, the key features of the MSLC mining system include a surface ramp connecting the levels to surface, a surface crown pillar separating the underground mine from the ground surface, and a backfill system consisting of a dedicated level from which a number of fill raises ends are used to fill the void created by production. One or more level accesses (LAC) are driven from the ramp on each level to access the orebody and enable sill drive development. Fig. 2 displays a schematic of a typical MSLC system. Distinct from the conventional approach, the MSLC mining system uses a crown pillar to separate the underground workings from an existing mined-out open pit or the surface environment. The crown pillar serves to eliminate the challenge of dealing with possible inrushes into the mine. The crown pillar is designed and supported with cable bolts to achieve a long-term stand-up time that could be beyond the life of mine to avoid surface subsidence [26].

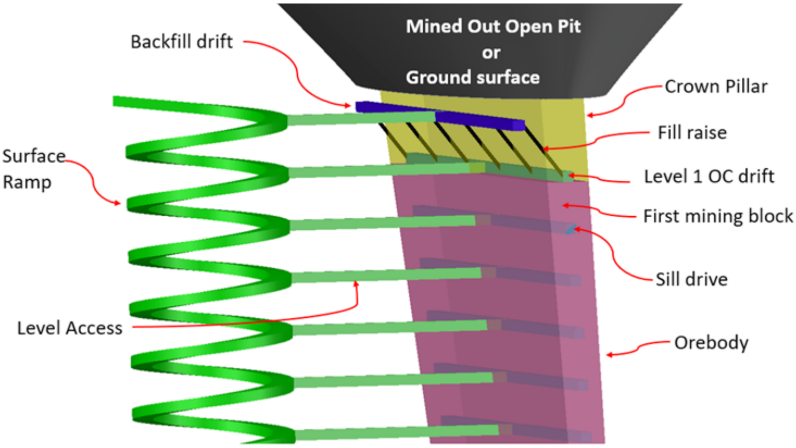


Fig. 2. Schematic of a Typical MSLC Mining System

The underground mine is accessed by a ramp system that serves a series of level accesses that are driven at uniform vertical intervals and perpendicular to the strike of the orebody. From the topmost level access, a footwall drift – called the backfill drift – is driven along the strike of the orebody at a geotechnically safe distance from the crown pillar to ensure long-term stability. A series of waste passes are driven diagonally at uniform intervals from the backfill drift to connect to the overcut drift at the top of the first mining block. Sill drives are then driven along the strike through the orebody.

2.2. Mine Design

Depending on the thickness of the orebody, one of three main design alternatives could be employed to mine the orebody. The first design layout is the longitudinal double retreat with a single sill drive and crosscut as shown in Fig. 3. This layout is usually used for tabular deposits with thicknesses ranging from 6 m to 10 m where a single sill drive runs through the orebody along the strike. The second design layout is the longitudinal double retreat with twin sill drives and a single crosscut as shown in Fig. 4. This layout is employed for wide orebodies with thicknesses around 15 m where two sill drives are required for reasons of ground stability. The third design layout is the transverse stoping as shown in Fig. 5. This layout is used for wider orebodies with thicknesses greater than 15 m where a series of crosscuts are driven off the haulage drift perpendicular to the orebody strike and extended across the orebody (sill drives) at uniform intervals. Ideally, the length of the crosscut which represents the stand-off distance from the orebody is determined from rock mechanics considerations. The sill drives are used for retreat mining towards the footwall. However, the longitudinal double retreat layout with multiple sill drives is the most preferred even for orebodies with thicknesses greater than 15 m.

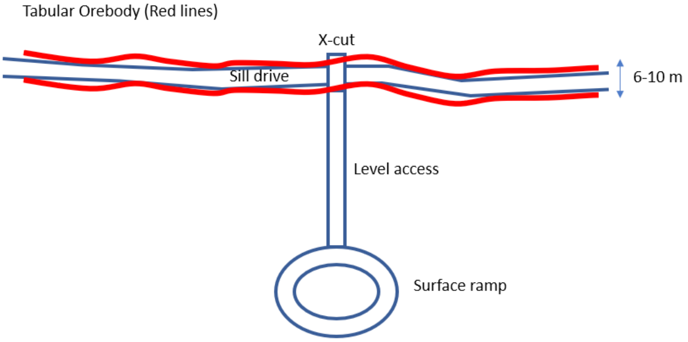


Fig. 3. Longitudinal Double Retreat with Single Sill Drive Layout

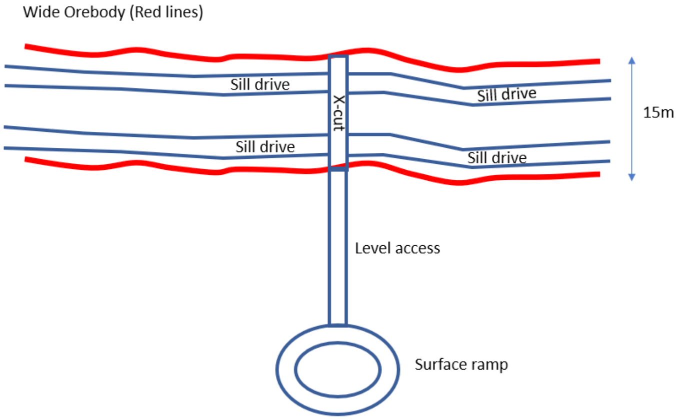


Fig. 4. Longitudinal Double Retreat with Twin Sill Drive Layout

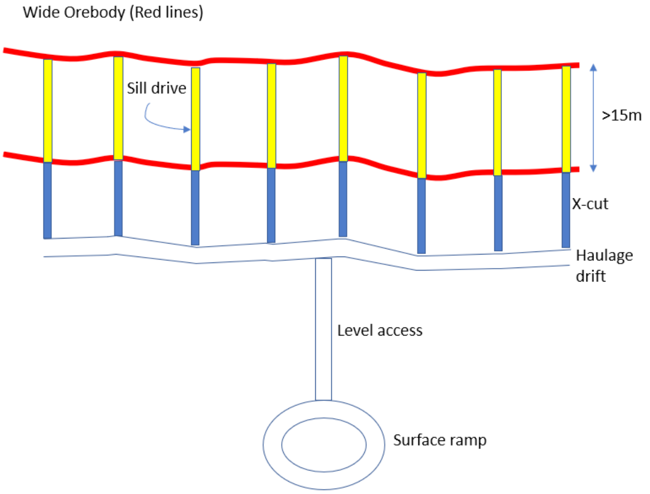


Fig. 5. Transverse Stoping Layout

2.3. Development of MSLC Mining Level

As ramp development from the ground surface reaches a particular mining level, a turn-off is made to allow for the development of the level access as shown in Fig. 6. The typical components of a level access include a level sump to collect mine water and pump it up to surface through pipelines, a return air raise (RAR), through which foul air from the working areas on the mining level is drawn by the primary exhaust fan sitting on surface, and a remuck bay to stockpile blasted ore and to serve as truck-load-out station. An escape way (manway), which connects to other escape ways on the upper levels is also developed to serve as a second egress out of the mine in times of emergency.

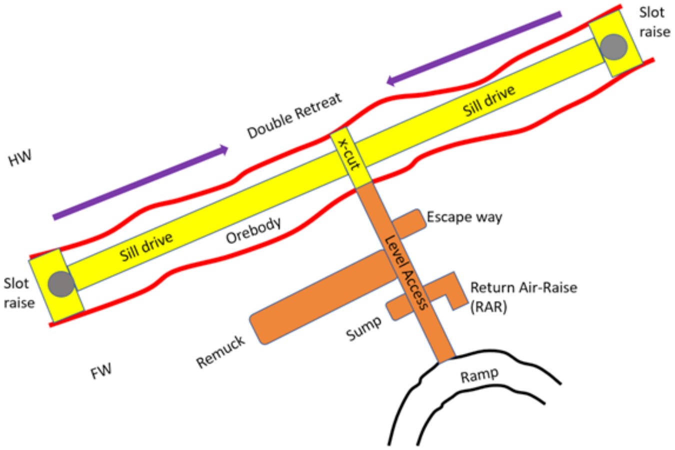


Fig. 6. Development of MSLC Mining Level

The level access is extended across the orebody by developing a crosscut from the footwall contact to the hanging wall contact. A long sill drive is driven longitudinally through the orebody to the extreme ends (end of value) where slot raises are established. The slot raises are blasted, and the mining sequence occurs in a double retreat manner towards the center of the orebody. All these developments are repeated on each mining level.

2.4. Mine Ventilation

The mine is ventilated using a pull system as shown in Fig. 7. The Primary exhaust fan mounted at surface on top of the main RAR draws the return air from the breakthrough area through the RAR on every mining level. This condition naturally draws fresh air from the mine portal through the surface ramp. A secondary fan is mounted at the shoulder of the ramp about 20 m away from each level access and ramp intersection; it pulls fresh air from the ramp and pushes it through flexible ventilation ducts that run to the working areas. The suction pressure existing at the breakthrough area of the RAR on the mining level causes the exhausted air to return from the working areas, through the RAR and up to the surface.

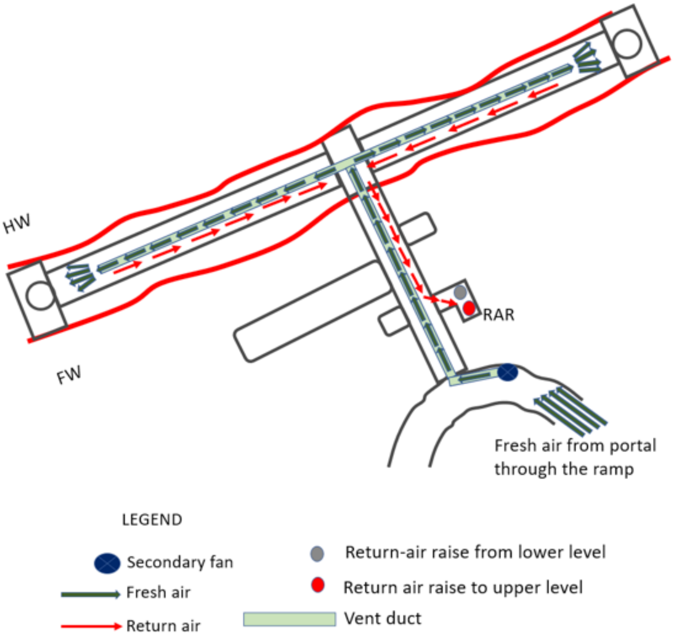


Fig. 7. Schematic of Mining Level Ventilation

2.5. Equipment Selection

Owing to its high level of mechanization, the MSLC mining method allows for the use of large-capacity equipment. In terms of development, one basic piece of equipment required for face advance is the jumbo drill. Rock bolters and cable bolters could be employed for ground support activities. In terms of production, an ITH drill or Raise borer is used to establish the slot raise at both ends of the sill drive. A long-hole drill rig to be set up in the sill drive is required for drilling production holes (uppers) in a ring pattern around and in between the two slot raises. An Explosive charge truck suitable for charging up-holes is required for charging and blasting the rings. LHDs and trucks make up the preferred haulage fleet as the mining method relies on ramp system for ore transportation.

2.6. Mining and Backfilling

After the development of the backfill drift, level 1 overcut (OC), level 1 sill drive, and backfill raises as shown in Fig. 8a, slot raises are established at the extreme ends of the sill drive. Production holes are then drilled to bring the first mining level to production.

A critical component of the MSLC mining method when production starts, is the mining and backfilling sequence as demonstrated in Fig. 8b to Fig. 8f. After blasting the slot raises as shown in Fig. 8b, the ore material is mucked out and backfilled with waste rocks from level 1 OC using an LHD equipment as shown in Fig. 8c. The first ring of production holes closer to the slot raise is then blasted, mucked out, and backfilled with waste rocks as shown in Fig. 8d and

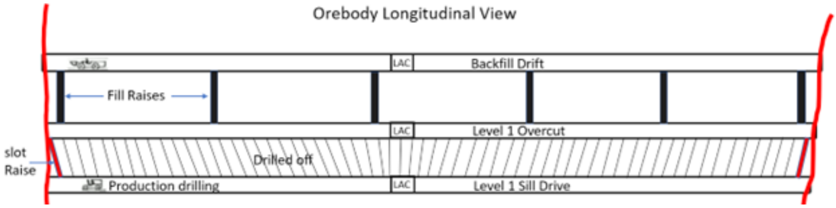


Fig. 8a. Preparation for Early Production

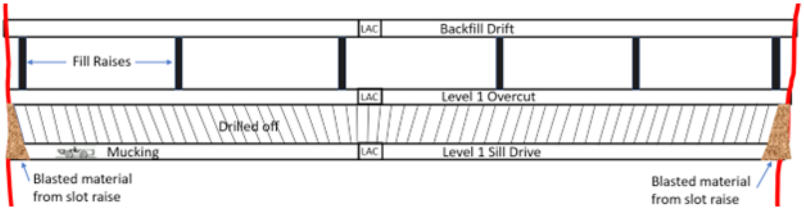


Fig. 8b. Slot Raises Blasted

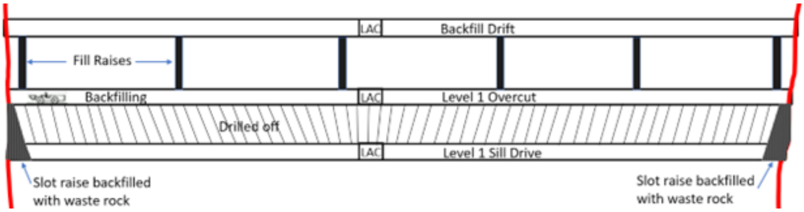


Fig. 8c. Backfilling Slot Raises

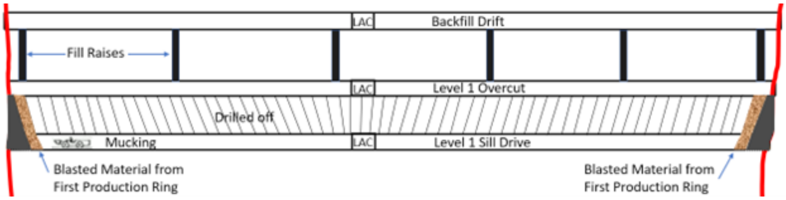


Fig. 8d. First Production Ring Blasted

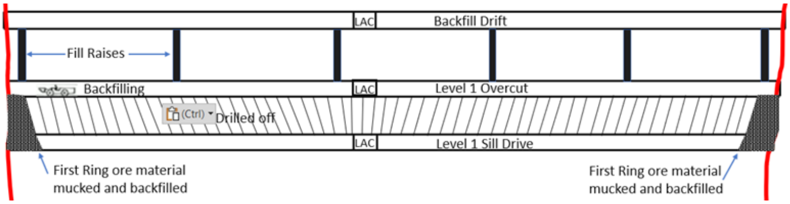


Fig. 8e. Backfilling Ring 1 void

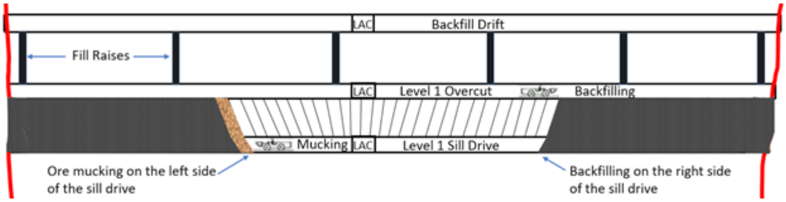


Fig. 8f. Concurrent Mining and Backfilling Activities

Fig. 8e. The subsequent rings of production holes are blasted to continue the same mining and backfilling sequence in a retreating manner as shown in Fig. 8f. While mining and backfilling activities are ongoing on the first mining level, development and production drilling at the lower levels continue unabated to prepare more levels for production as shown in Fig. 9.

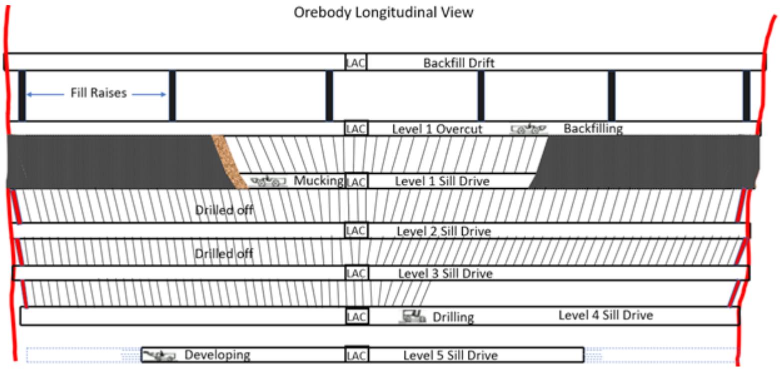


Fig. 9. Ongoing Development and Production Drilling at Lower Levels

As more levels become ready for production, mining activities on the immediate lower levels can commence as shown in Fig. 10 without leaving sill pillars between them to allow continuous and even flow of the backfill material down to the lower levels. This makes the MSLC method a multi-level mining method without the use of sill pillars. At this stage, backfilling is done from both level 1 OC and backfill drift through the fill raises. When mining level 1 is completed, the backfilling activity at level 1 OC ceases. All backfilling activities take place through the fill raises on the backfill drift as shown in Fig. 11. To avoid hang-ups in the fill raises, the fill material should be of uniform size not exceeding 1/6 of the fill raise diameter. Additionally, the fill material should be dry, as wet materials could consolidate or arch in the caved zone impacting its flowability.

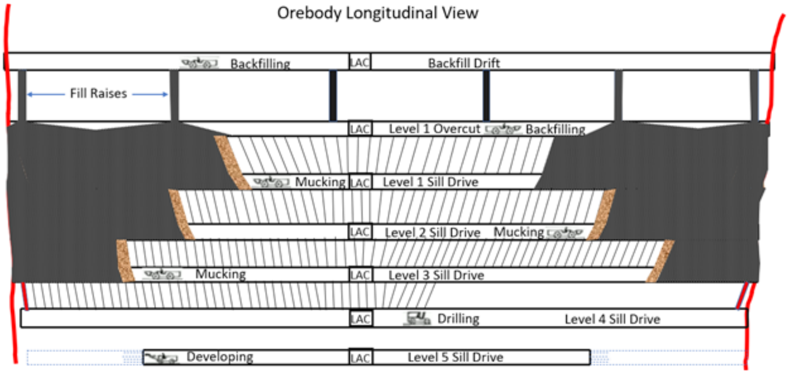


Fig. 10. Multi-level Mining

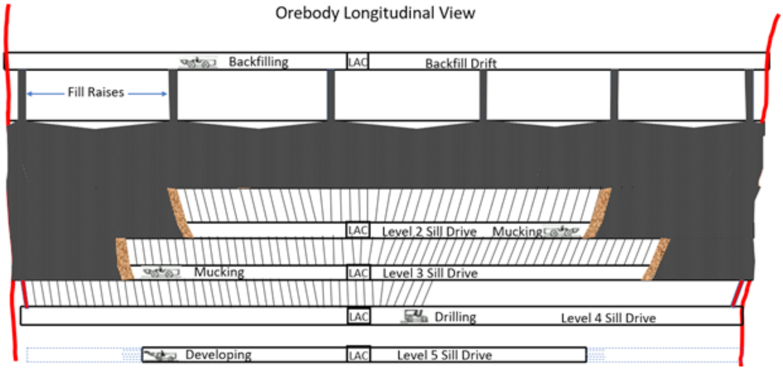


Fig. 11. Mining Level 1 Completed

A well-ordered multi-level mining sequence is essential to prevent undermining upper levels still in production. To do this, the production front at the upper level must advance away from that of the immediate lower level as shown in Fig. 10. The "stand-off" distance, which is the minimum horizontal distance between the brow of the upper and lower levels must be at least 5 rings of production holes for a safe multi-level mining operation.

2.7. Materials Handling

The preferred materials handling system for the MSLC mining method is the LHD-Truck system owing to the method's reliance on the ramp system for ore transportation. As shown in Fig. 12, the LHD travels between the draw-point and the remuck. When a haulage truck has arrived, the LHD will load it at the truck load-out station. It is imperative to ensure that the LHD is selected to match the truck capacity while satisfying the production requirement of the mine plan. This equipment matching is to ensure that the LHD completes a truck payload in 3-5 passes. Since material handling takes place on the same mining level using the LHD-truck combination, there is no requirement for the development of ore passes in this mining method.

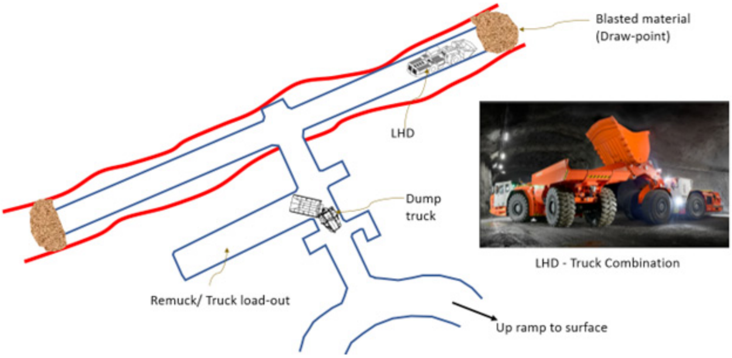


Fig. 12. Materials Handling Layout

2.8. Cycle Time and Productivity

From the perspective of mine planning, it is essential to determine the overall cycle time of the LHD to determine its productivity. This in turn helps determine the stope cycle and daily production rate. To determine the LHD cycle time, two scenarios are considered to estimate the lowest and highest possible LHD daily productivity. Fig. 13 demonstrates scenario 1 representing the lowest possible productivity where the LHD must travel to the slot raise location for mucking. For the purpose of this study, the orebody is assumed to have a strike length of 500 m. After blasting the slot raise, the total distance between the draw-point and the truck load-out station is 290 m. Given the cycle time parameters in TABLE 1, the LHD round trip is estimated at approximately 4 minutes per round trip. Considering two 10-hour shifts per day which is commonly practiced in Canadian mines, and assuming 7 working hours per shift with job efficiency of 50-55 mins/hr, it can be shown that the LHD productivity for scenario 1 is 1,577 tpd (tonnes per day).

TABLE 1

LHD Cycle Time Parameters

Bucket Capacity	Fill Factor	Muck Density	Load Time	Travel Speed (loaded)	Dump Time	Travel Speed (empty)
5.3 m^3	90%	1.9 t/m^3	30 s	10 km/h	30 s	14 km/h

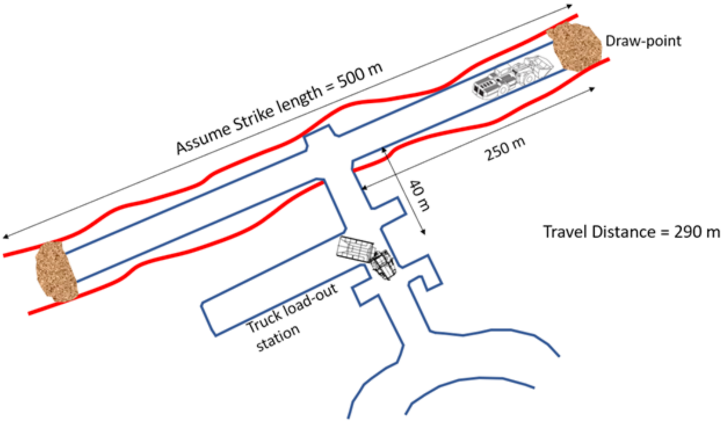


Fig. 13. LHD Cycle – Scenario 1

As mining retreats towards the center of the sill drive, the travel distance between the draw-point and the truck load-out station decreases as shown in Fig. 14. Considering a travel distance of 40 m from the center of the sill drive to the truck load-out station, and using the same parameters listed in TABLE 1, the LHD round trip is estimated at approximately 1.5 minutes per round trip. Thus, the LHD productivity for scenario 2 is 4,183 tpd.

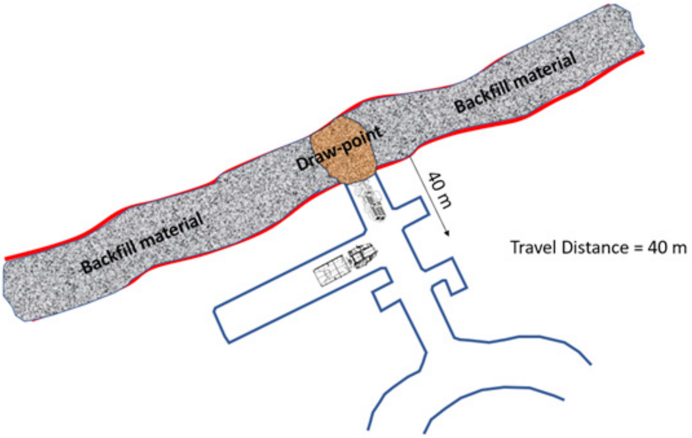


Fig. 14. LHD Cycle – Scenario 2

Comparing the daily LHD productivity per day from the two scenarios, it is obvious that the mucking rate will increase as the mining operation retreats towards the center of the sill drive. Fig. 15, which plots the LHD productivity versus the haulage distance, can be used as a basis for estimating the daily production rate of the operation from multiple levels. For the system depicted in Fig. 15 with 5 active production levels, it is reasonable to expect a high daily production rate greater than 6,000 tpd, albeit subject to the ramp haulage capacity.

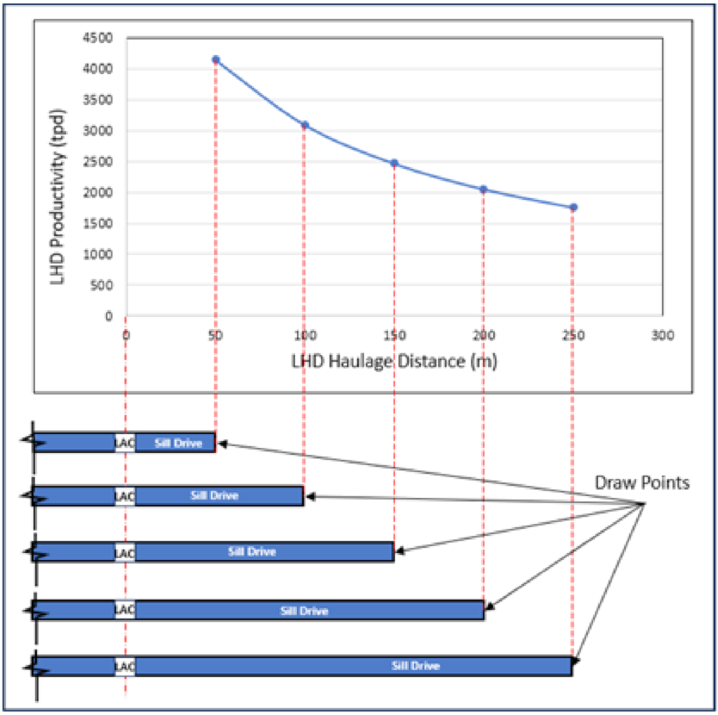


Fig. 15. LHD Daily Productivity vs Haulage Distance

2.9. Dilution Control and Geomechanics Issues

All mining methods suffer some level of dilution and geomechanics issues. The severity of the geomechanics issues is largely dictated by the in-situ stress regime of the mining environment. High levels of dilution and in-situ stresses pose significant challenges to any mining operation if not properly managed. In this study, dilution control and the impact of in-situ stress regime on the MSLC mining method are discussed and demonstrated by ways of reference to a real-life mine case study.

3. Mine Case Study 1 – Chirano Gold Mines Limited

In this section, the Chirano Gold Mines Limited in Ghana, West Africa, which is a subsidiary of Kinross Gold Corporation in Canada is selected as a case study to demonstrate the benefit associated with the application of the MSLC method. The Paboase underground mine of Chirano Gold produces an average of 6,000 tpd (tonnes per day) from a steeply dipping orebody that is extracted with the MSLC method. The design layout used was the longitudinal double retreat with twin sill drives at the upper levels which was later switched to a single sill drive layout at the lower levels due to changes in orebody thickness. The following sections will discuss dilution control measures and stress conditions associated with the MSLC method at the Paboase mine.

3.1. Dilution Control

In the MSLC mining method, the introduction of waste rocks into the void to support the walls could lead to some level of dilution if not properly controlled. To alleviate this problem, the concept of "ore blanket" is introduced, in which a percentage of ore mucking at the first upper mining level is left behind to build a layer of blasted ore that separates mucking from overlying rockfill. This ore blanket technique was practiced by Chirano Gold Mines Limited at their Paboase underground mine and yielded good results. The purpose of the ore blanket is to prevent early contact of the rockfill with the ore material blasted from the subsequent lower levels. Thus, leaving an ore blanket is a deliberate attempt to have maximum control over dilution for a period of active production time on several mining levels until slightly more dilution is observed as mining progresses deeper, at which point a second ore blanket is utilized. The sequence of creating this "ore blanket" is demonstrated in Fig. 16. After blasting the slot raises on the first level, approximately 70% of the ore material is mucked out, leaving the remaining 30% in the stope to serve as blanket as shown in Fig. 16a. The void created atop the remaining 30% of ore material is backfilled with waste rocks as shown in Fig. 16b. The next ring is blasted, and the percentage mucking and backfilling sequence is repeated as shown in Fig. 16c. This sequence is repeated for all subsequent rings to be blasted, leaving a blanket of blasted ore material between

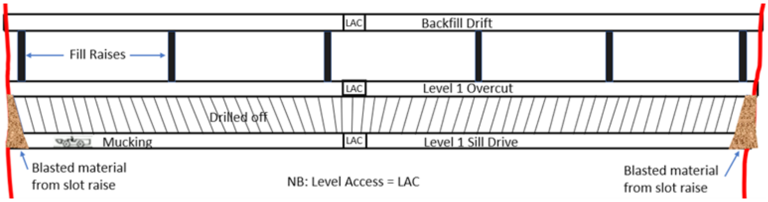


Fig. 16a. Percentage Mucking – Slot Raise

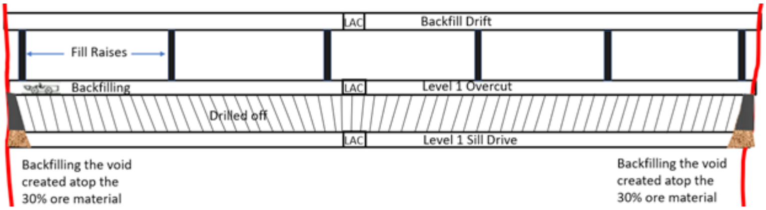


Fig. 16b. Percentage Backfilling – Slot raise

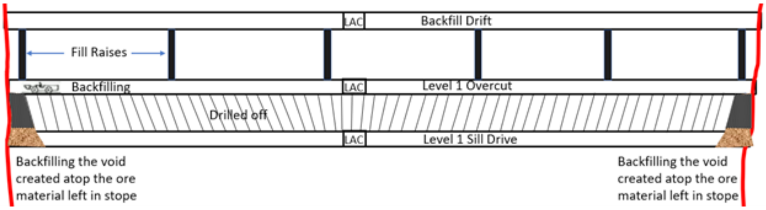


Fig. 16c. Percentage Backfilling – Ring 1

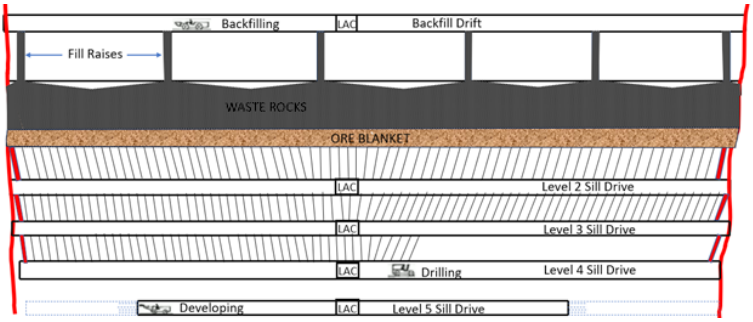


Fig. 16d. Ore Blanket

the rockfill and the next mining block as shown in Fig. 16d. The thickness of the ore blanket may be increased further by slightly reducing the percentage of ore material to be mucked from the immediate lower level. When the desired ore blanket is achieved, a 100% mucking rate could be done on the subsequent lower levels as mining progresses deeper. The ore blanket moves with the downward progression of mining activities as shown in Fig. 17.

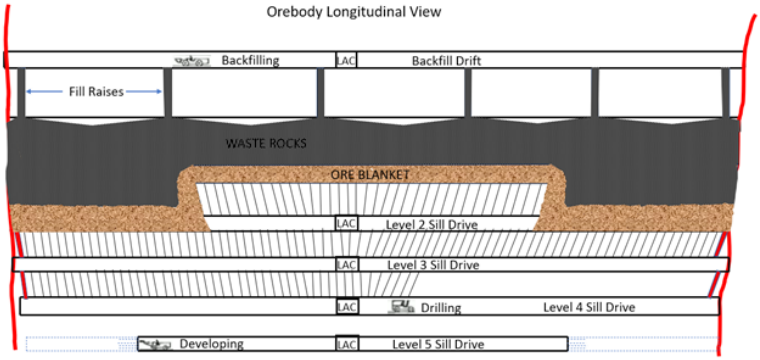


Fig. 17. Ore Blanket Movement

It is however noteworthy that the approximately 30% of ore left in the stope to create the ore blanket only happens at the first upper level and not at every level of the entire mine since the ore blanket moves downwards to the lower levels as mining progresses deeper. As such, the ore blanket is only recreated on one of the lower levels when some evidence of dilution is observed because of the continuous downward movement. It is also worth mentioning that the ore blanket is recovered or mucked out at the bottom level during mine closure albeit at a low grade due to some level of dilution that might have occurred.

3.2. Numerical Modeling of Pillar Stress Condition

Although preferred for the MSLC method, the longitudinal double retreat mining sequence creates diminishing mining blocks or pillars while approaching the center of the orebody. These pillars are usually exposed to high horizontal mining-induced stresses which may lead to strain bursts depending on the rock mass geo-mechanical properties and in-situ stress regime. To examine the stress state in these pillars, a stress analysis is performed through mine-wide numerical modeling.

3.2.1. Mine-wide model construction

The orebody of the Paboase underground mine extends to 1 km below the ground surface. It strikes in the NS direction with a strike length of 500 m at the top and 140 m at the bottom and dips at 85°E. The orebody varies in thickness from 20 m wide at the top to 6m wide in the deeps, with slightly uniform thickness along the strike. Due to the varying thicknesses of the orebody, the longitudinal double retreat with twin sill drive layout was adopted for the upper levels and single sill drive for the lower levels.

To build the large-scale 3D numerical model, CAD software Rhino 7 is used to construct the model surface geometry. The surface mesh of the model is converted to a solid body grid using Griddle 2.0 plugin released by Itasca company, as shown in Fig. 18. The 3D finite difference code FLAC3D 7.0 from Itasca is then used to perform the stress analysis. As shown in Fig. 19, the model encompasses the hanging wall, footwall, and orebody. A large part of the orebody has been mined out at the upper levels and backfilled with waste rocks, leaving the crown pillar and a few production levels in the deeps (1 Km) to demonstrate the effect of stresses on the diminishing pillars due to the mining sequence. The rockfill and host rock contact is modeled as a weak shear interface with normal stiffness, Kn = 15 GPa and Ks = 100 MPa. This is to ensure that the waste rocks do not cling to the walls but freely move down to exert their full weight on the mining blocks as happens in practical terms. The model is 2000 m in height, 1500 m in length, and 1100 m in width. The *x*- and *y*-directions in the model correspond to east and north, respectively.

3.2.2. Rockmass Properties of Chirano Mine

Rock samples were collected from the hanging wall (HW), footwall (FW), and the orebody, and their mechanical properties estimated from uniaxial compressive tests. Average values of

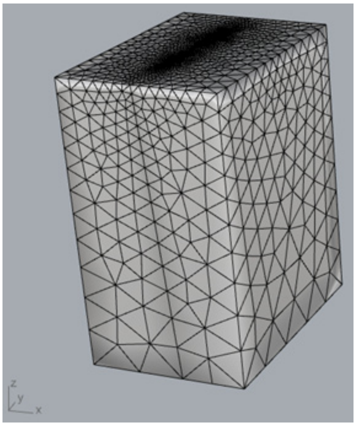


Fig. 18. Isometric view of the Rhino model

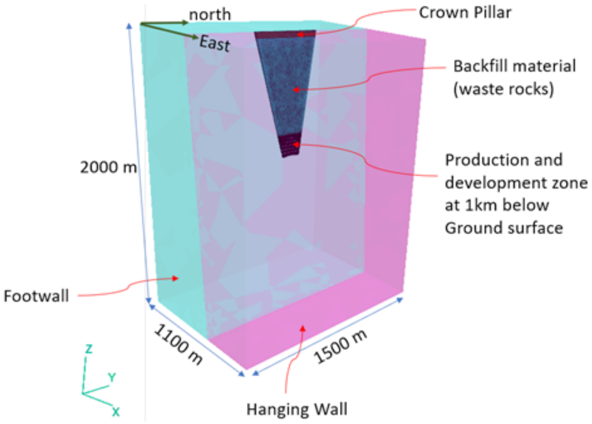


Fig. 19. Isometric view of FLAC3D mine-wide model

the experimental results, including the intact modulus of elasticity, E_{intact}, Poisson's ratio, v, unit weight, γ, and uniaxial compressive strength, σ_c, are presented in TABLE 2. It is noticed from the table that the uniaxial compressive strength of the orebody is comparatively high, making it capable of storing high elastic energy. The rockmass rating (*RMR*) system developed by Bieniawski [27] was used to classify the orebody and host rocks. The *RMR* results obtained are 73, 74, and 74 for the HW, FW, and orebody, respectively. Using the *RMR*, the modulus of elasticity of the rockmass, E_{rm}, can be calculated using the equation proposed by Mitri et al. [28].

$$E_{rm}\left(GPa\right) = 0.5E_i\left[1-\cos\pi\left(\frac{RMR}{100}\right)\right] \tag{1}$$

TABLE 2

Rockmass Properties of Chirano Mines

	E_{intact}, (GPa)	E_{rm}, (GPa)	v	γ (KN/m^3)	σ_c (MPa)	C (MPa)	Ø (°)
HW	78.3	64.9	0.23	27.4	116	—	—
FW	64.0	54.0	0.23	27.4	186	—	—
Orebody	69.0	57.8	0.23	27.4	223	—	—
Backfill	—	0.20	0.3	26.0	—	0	35

3.2.3. In-situ stress and boundary condition

The stress regime of the West African region is generally considered low compared to other tectonically active regions [29]. In-situ stress measurements conducted by SRK Consulting in the Paboase deeps (1 km) of Chirano Mines indicated that Sigma-1 and Sigma-2 are almost sub-horizontal with a plunge of 30° and 20°, respectively. The Sigma-3 is almost sub-vertical. The ratios of Sigma-1 to Sigma-3 and Sigma-2 to Sigma-3 are 1.73 and 1.17, respectively. The vertical stress gradient is 0.0274 MPa/m. Sigma-1 stress acts perpendicular to the orebody strike. Regarding boundary conditions, roller boundaries are applied to the bottom of the model and each of its four vertical sides. A minimum constraint is applied to the outer boundaries of the model to avoid the development of undesired local stress concentrations near the boundaries. While gravity is applied as a body force, horizontal-to-vertical stress ratios are applied to the domain to initialize in-situ stresses.

3.2.4. Stress Analysis of the Diminishing Pillars

In FLAC3D, the orebody is mined and backfilled using the MSLC mining and backfilling sequence. The stress contours in the mining blocks are shown in Fig. 20. It is noticed that the diminishing mining blocks suffer high horizontal mining-induced stresses as the mining operation approaches the center of the sill drive with the most diminished pillar recording an average Sigma-1 stress of 118 MPa. This is not seen in the mining blocks yet to be mined which record an average Sigma-1 stress of 45 MPa. It is worth mentioning that the size of the most diminished mining block at the first production level as seen in Fig. 20 is about 16 m in strike length, which is the width of the level access (LAC) plus two production rings on both sides of the sill drive as demonstrated in Fig. 21. Practically at Chirano mines, the retreating mining sequence stops when the pillar reaches this size and is treated as a mass blast also known as intersection blast.

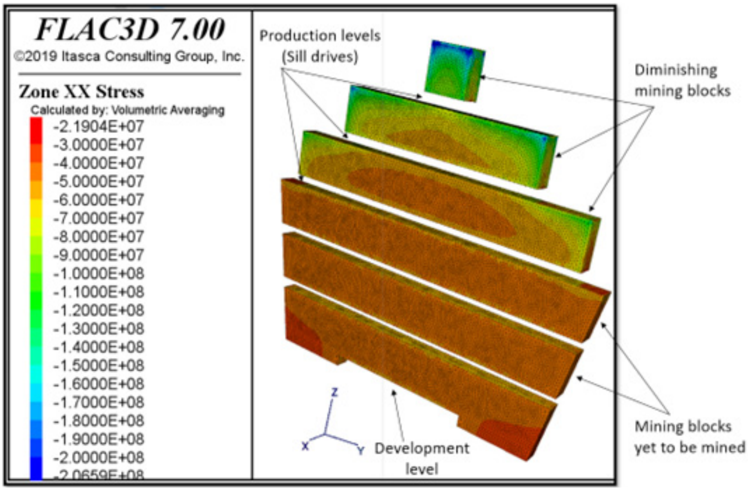


Fig. 20. Mining Induced Horizontal Stress Distribution in Diminishing Mining Blocks – Chirano Mine Model. NB: HW, FW, and BF are hidden

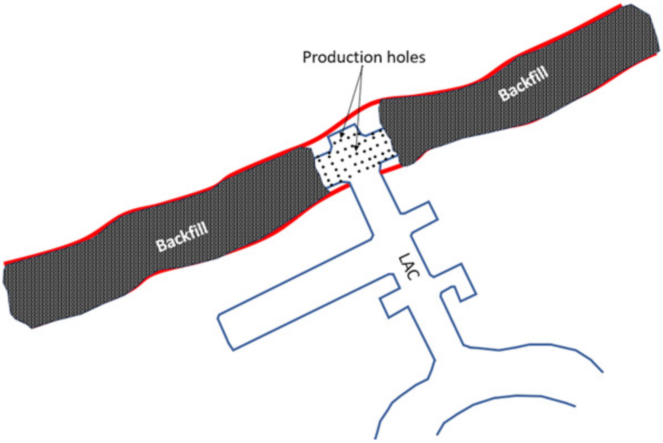


Fig. 21. Sill Drive-Level Access Intersection Blast

It is also noteworthy that the analysis is carried out with linear elastic materials. This is not uncommon when examining the potential for rockburst in mine stability analyses [30]. Therefore, to assess the impact of the high horizontal mining-induced stresses in the diminishing mining blocks on the safety of the mining operation at the production levels, the Brittle Shear Ratio (*BSR*) criterion is used to determine the potential for strain bursting in these mining blocks. The *BSR*, which is the ratio of the differential mining-induced principal stress ($\sigma_1 - \sigma_3$) to the

TABLE 3

Potential for Strain Bursting Based on BSR (Castro et al., 2012)

BSR	Rock Mass Damage	Potential for Strain Bursting
0.35	No to Minor	No
0.35 to 0.45	Minor (e.g. Surface Spalling)	No
0.45 to 0.6	Moderate (e.g. Breakout formation)	Minor
to 0.7	Moderate to Major	Moderate
>0.7	Major	Major

uniaxial compressive strength of the intact rock (σ_c) is expressed by Eq. (2) and it summarizes the potential for rock damage in TABLE 3 [31].

$$BSR = \frac{\sigma_1 - \sigma_3}{\sigma_c} \tag{2}$$

Stress analysis in the mining blocks suggests that although the diminishing blocks suffer high horizontal mining-induced stress, the BSR values recorded in the back, shoulders, and stope brow at the production levels are within acceptable limits as shown in Fig. 22. This could be attributed to the low tectonic stress regime of the West Africa region as well as the high UCS value of the orebody making it capable of taking up high mining-induced stresses. It is worth noting that the development areas below the production zone in the Paboase deeps at Chirano mine experienced minor seismic events from the 1450 level down to the 1400 level. However, field investigations and analyses showed that these seismic events were primarily due to the presence of a weak hanging wall shear at those levels and not a consequence of the mining method.

Furthermore, the stability of the HW is checked with BSR as shown in Fig. 23. As can be seen, the BSR values are well below the 0.7 limit suggesting little or no potential for brittle burst failure. The low BSR values can be attributed to the confinement offered by the backfill material, which is clearly a feature of the MSLC. It is worth mentioning that the findings of the

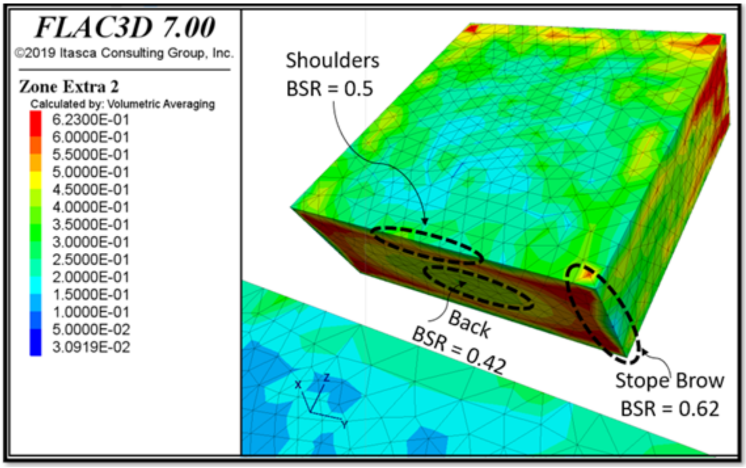


Fig. 22. Computed BSR Values in the Mining Blocks

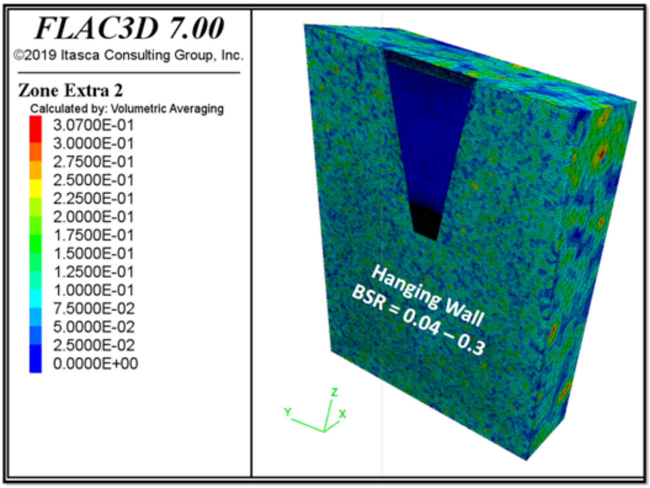


Fig. 23. Computed BSR Values in Hanging Wall

model corroborate well with real mine site observations at the Paboase underground mine which operates to a level of approximately 1 km below ground surface using the MSLC mining method.

4. Mine Case Study 2 – Copper Cliff Mine

For the sake of comparison, the MSLC mining method is modeled in the Canadian shield which has a relatively higher stress regime compared to that of the West African region. The data on In-situ stresses and rock mass properties were taken from the study by Sainoki et al. [32] on Copper Cliff Mine in Sudbury, Canada. Copper Cliff mine employed the sublevel stoping mining method and not the MSLC mining method, and serves as a demonstration of the suitability that the MLSC mining method would have exhibited if chosen. The same orebody geometry and model size presented in the previous section are used in this case study.

4.1. Rockmass Properties of Copper Cliff Mine

The material properties of the rockmass in Copper Cliff Mine are presented in TABLE 4. It is noticed that the uniaxial compressive strength of the orebody is comparatively low – almost half the UCS value of the orebody at the Chirano mine. This could make it incapable of taking up high mining-induced stresses due to the high in-situ stress regime of the Canadian shield.

TABLE 4

Rockmass Properties of Copper Cliff Mine (Sainoki et al., 2016)

	E_{intact}, (GPa)	E_{rm}, (GPa)	v	γ, (KN/m^3)	σ_c, (MPa)
Host rock	52	37.8	0.24	28.5	94
Orebody	38	27.6	0.28	36.3	78

4.2. In-situ Stress Regime

Calibration of the pre-mining stress state was carried out by Sainoki et al. [32] based on the stress-depth relationship used at the Copper Cliff mine. This was done based on stresses calculated from Eqs. (3) to (5). From their calibration results, the stress-depth relationships were almost identical to those proposed by Herget [33] and Diederichs [34].

$$\sigma^0_{H_{\max}} = 0.0407 \times D + 10.35 \tag{3}$$

$$\sigma^0_{H_{\min}} = 0.0326 \times D + 8.69 \tag{4}$$

$$\sigma^0_v = 0.029 \times D \tag{5}$$

Where D is the mining depth in meters. Considering 1 km mining depth as in the case of Chirano mines, the maximum and minimum horizontal to vertical stress ratios are estimated to be 1.8 and 1.4, respectively.

4.3. Stress Analysis of the Diminishing Pillars

Following the same modeling procedures in Section 3, the stress contours of the mining blocks in the MSLC mining sequence are shown in Fig. 24. As expected, it is noticed that the diminishing mining blocks suffer high horizontal mining-induced stresses as the mining operation retreats towards the center of the sill drive.

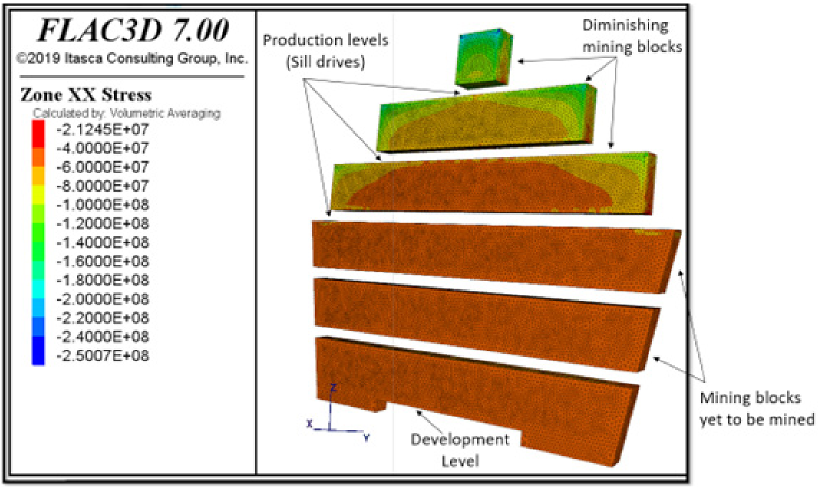


Fig. 24. Mining Induced Horizontal Stress Distribution in Diminishing Mining Blocks – Copper Cliff Mine Model. NB: HW, FW, and BF are hidden

However, contrary to the low BSR readings in the mining blocks in Chirano mines, the BSR readings in the Copper Cliff mine model are considerably high and beyond the acceptable limits for strain bursting as shown in Fig. 25. This could be attributed to the high tectonic stress regime of the Canadian shield coupled with the considerably low UCS value of the orebody making it unable to take up high mining-induced stresses leading to strain bursts.

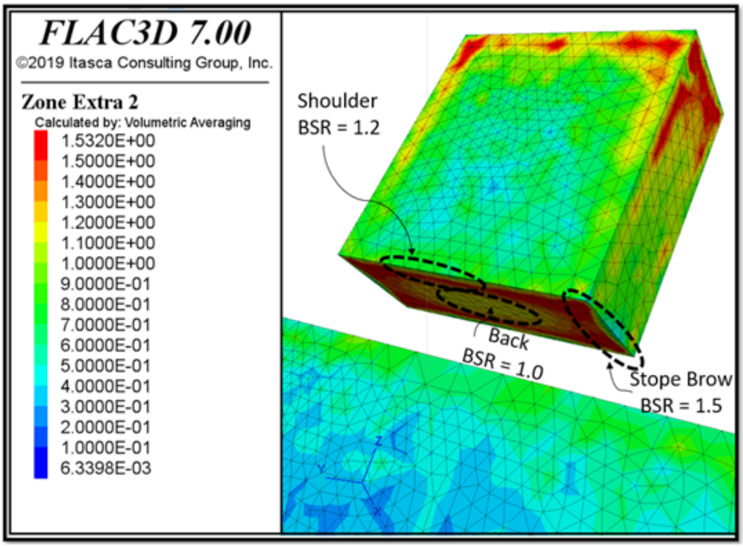


Fig. 25. Computed BSR Values in the Mining Blocks – Copper Cliff Mine Model

The BSR results from the two case studies suggest that the MSLC mining method may suffer strain burst challenges when applied in regions of high tectonic stresses. This is primarily due to the creation of diminishing pillars resulting from the mining sequence. To solve this problem, a center-out mining sequence is adopted. That is, instead of mining from the abutments towards the center of the orebody, mining is done from the center of the orebody towards the abutments. In this case, two crosscuts would be required to access the far ends of the orebody. Details of mine development for the center-out system is beyond the scope of the current study.

The center-out mining sequence eliminates the creation of stand-alone pillars that are incapable of taking up high mining-induced stresses. The pillars in the center-out mining sequence are attached to the host rock as shown in Fig. 26. This way, the host rock takes up part of the mining-induced stresses, reducing the burst potential of the pillars. From Fig. 27, it is noticed that there is a significant reduction in BSR values to acceptable limits when the center-out mining sequence is adopted for a region of high in-situ stresses, making the MSLC mining method suitable to be applied in the Canadian shield.

5. Merits of the MSLC

Whereas the MSLC method enjoys all the advantages of the traditional SLC mining method including early access to ore recovery thereby reducing the payback period, multilevel mining operation leading to high production rates, low backfill cost, and continuous stoping without inter-

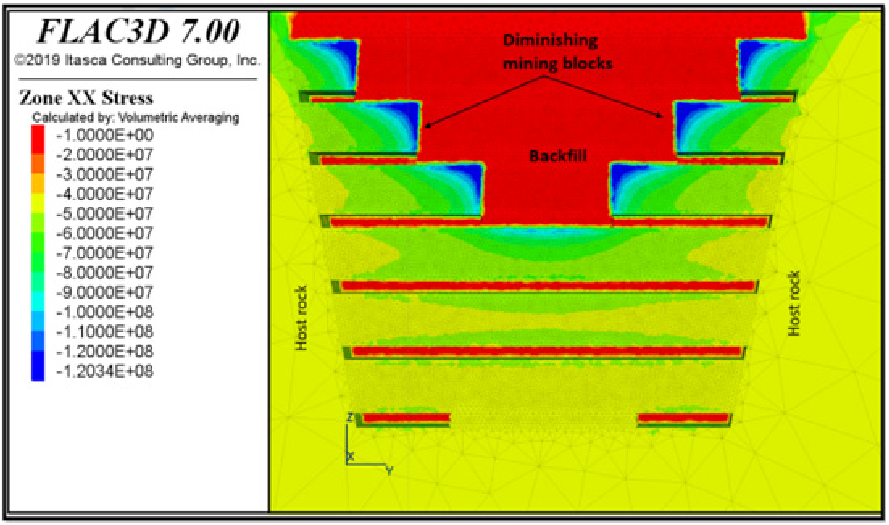


Fig. 26. Center-Out Mining Sequence – Copper Cliff Mine Model

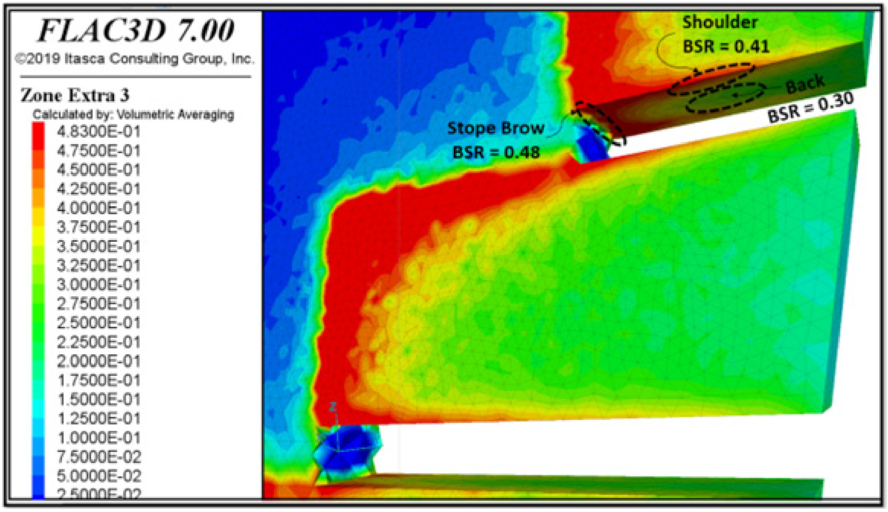


Fig. 27. BSR Values for a Center-Out Mining Sequence – Copper Cliff Mine Model

rupting the mining cycle, it also boasts several benefits. The introduction of a well-designed and supported crown pillar in the MSLC method prevents the occurrence of ground surface subsidence. Air blast is avoided due to the prevention of the sudden movement of the host rock walls by the continuous backfilling of the void created atop the mining zone with waste rocks to support the walls. The devastating consequences of inrushes are avoided owing to the use of a crown pillar to separate the surface environment from underground activities. Unlike the traditional SLC mining method which requires additional developments such as ore passes, main haulage level, internal ramps, and lots of slot raises, the MSLC method requires only a few developments to prepare a mining level for production leading to a significant reduction in development cost.

6. Conclusions

In this study, it is shown that the MSLC has several advantages over the traditional SLC such as the avoidance of ground surface subsidence, reduced dilution, as well as the elimination of potential air blasts and inrushes. The MSLC mining method provides exceptional solutions to these challenges, and these are demonstrated by way of reference to real-life mine case study. The following conclusions can be drawn from this study.

1) The Modified Sublevel Caving (MSLC) method is applied to moderate to competent rockmass where caving of the host rock is not possible and/or undesired.
2) The issue of high ore dilution in the traditional SLC method has been addressed using the ore blanket technique which yielded good results when practiced in Chirano Gold Mines Limited.
3) Productivity is enhanced due to the benefit of multilevel mining without the use of sill pillars and its associated recovery challenges.
4) The modeling results indicate that the application of MSLC in Chirano mine did not pose any seismic threats to the mining operation. This is attributed to the comparatively low in-situ stress regime of the West African region as well as the competency of the Paboase orebody. However, in regions of high in-situ stresses like the Canadian Shield, the MSLC method could cause seismic problems if the diminishing pillars are incapable of taking up high mining-induced stresses. This may be avoided by adopting a center-out mining sequence which significantly reduces the burst potential of the diminishing pillars in high in-situ stress environments.
5) With the ground surface ecology kept undisturbed, the demonstrated MSLC mining method is in line with sustainable practices for future mining that call for reduced footprint.

Acknowledgment

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