Underhand Cut and Fill Mining as Practiced in Three Deep Hard Rock Mines in the United States

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Abstract

Underhand cut and fill mining methods are used at the Lucky Friday, Stillwater, and Galena mines in the western US in an effort to safely mine in difficult ground conditions and as a primary mining method where access below the ore is limited. The method has evolved at each mine to meet the unique situations associated with their milling procedure and mine layout. Details of the operational aspects of the backfilling and mining cycles at each mine are presented in this paper, accompanied by a summary of the mechanical properties of the backfill and its in-situ geomechanical behavior.

1.0 Introduction

The introduction of underhand cut and fill mining in the 1980s made hard-rock mining in hazardous ground conditions safer (Marcinyshyn, 1996). Underhand mining uses cemented mill tailings for backfilling the mined-out stope cut, making the mining process in the following cuts safer because the miners are always working beneath a reinforced cemented-backfill that will not fall during a rockburst. In 1980, Hecla Mining Company, in cooperation with the US Bureau of Mines' (USBM) Spokane Research Center, conducted a test of underhand mining to recover a potentially rockburst-prone sill pillar at the Star Mine. The object of this test was also to protect miners from injuries caused by rock falling from the back (or roof) during a rockburst. This test demonstrated that underhand mining could work, but operational aspects of the method needed improvement. The areas in need of improvement were cemented backfill delivery and fill mat/support construction in the stope prior to backfilling. The cemented backfill delivery system used at the Star Mine delivered material to the stope in a medium-density slurry in which the fine cement particles were suspended in the excess water which was then decanted over the sand wall, resulting in inconsistent fill strengths. The sill mat construction technique was labor and material intensive.

Hecla began another test titled “Lucky Friday Underhand Longwall” (LFUL) in 1985 which also involved the USBM and the University of Idaho (Werner 1990, Brackebusch 1994). In this test, Hecla developed a paste-type backfill with no free water so that cement fines would not be decanted from the stope as it was filled. This research developed the vertically-placed #7 DYWIDAG bolt method, which is used for cemented mill-tailings backfill reinforcement in most mines today. This method reduced the time and cost of preparing the stope for cemented backfill significantly and made the underhand method a viable alternative to traditional overhand mining methods for steeply dipping veins.

The underhand design differs from the overhand cut and fill design (Figure 1) in that it requires the vertical installation of DYWIDAG rock bolts in loose rock on the floor of the mined-out stope cut in a predetermined pattern prior to backfilling the cut with cemented mill tailings. The next cut is mined beneath this fill, which becomes a reinforced concrete beam as the stope walls close upon it. The closure induces loads in the fill which are transferred to the vertical bolts as the fill deforms. The most important aspect of this method is the maintenance of a consistent fill quality; this includes percentage of solids, cement content, and placement. The proper combination of these factors is required so that the cemented tailings will develop enough strength to protect the miners working under it.

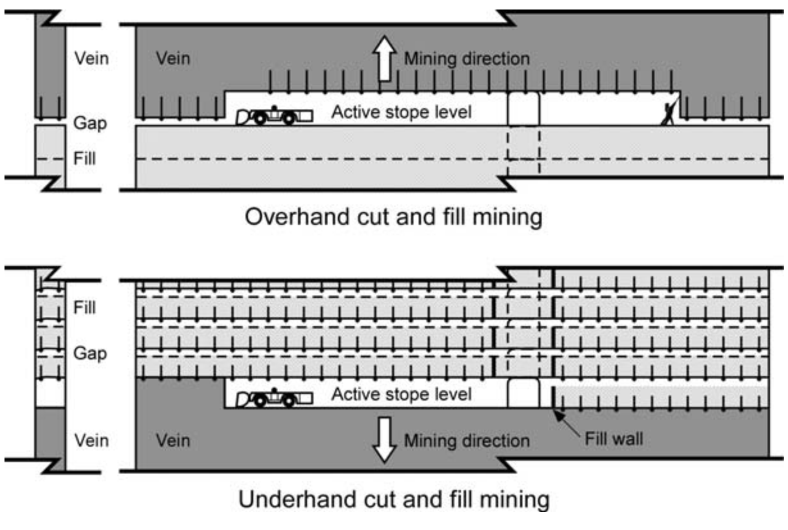

Figure 1. Comparison of underhand and overhand mining methods.

The underhand method effectively mitigates ground-fall injuries because the backfill created is capable of withstanding the shock of a rockburst, as demonstrated by a 3.5 Richter magnitude rockburst that occurred with blasting at the Lucky Friday Mine, Figure 2. The reinforced cemented fill in the back survived with some bagging while the fly rock from the walls was restrained by the chain link installed along the stope walls. Prior to converting to underhand mining, the Lucky Friday Mine experienced three rockburst-related fatalities in four years. However, in the 20 years since converting, a rockburst-related fatality has not occurred at the mine. In the Gold Hunter portion of the mine, underhand mining is now used by Hecla for production below the main access level. This allows for resource recovery without the expense of sinking the shaft. In 2001, as mining depths increased and ground conditions became more challenging, the Stillwater Mine also began using underhand cut and fill mining, consequently improving miner safety by reducing possible exposure to poor ground conditions and falling rock-related injuries—with the exception of the periods during initial sill development (Jordan et al., 2004).

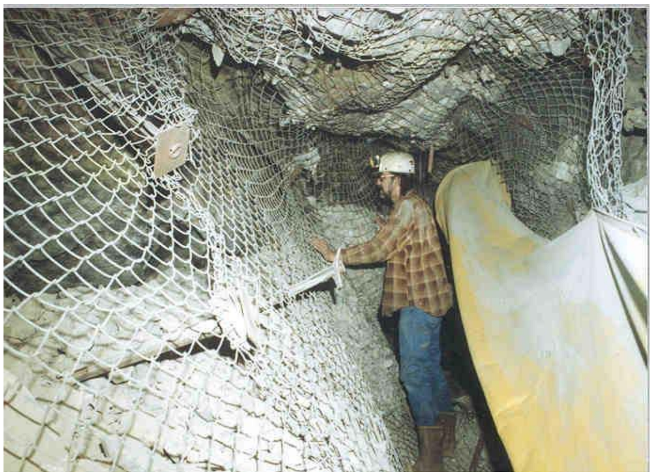

Figure 2. Underhand stope survives 3.5 ML rockburst.

Also in 2001, personnel from the Spokane Research Laboratory of the US Bureau of Mines' successor, the National Institute for Occupational Safety and Health (NIOSH), assisted the Galena Mine with the introduction of mechanized underhand cut and fill mining. The goal was to recover ore beneath the lowest level of the mine in an area where rockbursts had occurred and ground conditions were very poor. The initial stope was mined using the underhand method from the 5,500 level downward on a 70° dipping vein. When this stope proved successful, the mine began using the underhand method to recover other rockburst-prone sill pillars, which are typically conventional slusher-stopes with a 5-cap access raise or mechanized LHD stopes with ramp access.

Due to the early efforts of the USBM and the present efforts of NIOSH, there are now twelve mines in North America that use the underhand method when mining in difficult ground conditions (Pakalnis et al., 2006). All of the mines use either cemented mill tailings or cemented rock fill for backfilling, (Tesarick et al., 2003).

This paper discusses the similarities and differences between the underhand cut and fill mining methods used at the Lucky Friday, Stillwater, and Galena Mines in the northwestern US (Figure 3). Each mine has developed its underhand mining system to accommodate the unique circumstances of their respective mining sites. This discussion includes descriptions of each mines' backfill properties, delivery systems, stope preparation procedures for backfill, practices employed to mine the stopes under the backfill, and the geomechanics of the stope wall and backfill.

Figure 3. Location of the Galena, Lucky Friday and Stillwater mines.

2.0 Studies of Underhand Methodologies at Three Western Mines

2.1 Backfill Properties and Delivery

The backfill properties vary significantly between the Galena, Lucky Friday, and Stillwater mines (Table 1). The Lucky Friday Mine uses a tailing paste fill with no free water, and 8–10% cement that develops 2,070 kPa (300 psi) of unconfined compressive strength (UCS) after curing for seven days. The fill is delivered to the stope at a rate of 118 t/hr (130 stph), or 64 m^3/hr (85 yd^3/hr) (Table 2).

Similarly, the Stillwater Mine uses a total tailings paste fill with 10–12% cement that develops 586 kPa (85 psi) of UCS after seven days. The lower strength of the Stillwater fill results from the large amount of -44 micron (-325 mesh) particles in the mill tailings. However, the fine particles allow the use of a lower velocity in the horizontal pipelines, 0.64 m/sec (2.1 ft/sec) versus 2.29 and 2.35 m/sec (7.5 and 7.7 ft/sec) at the other mines. This is because the fines hold the larger particles in suspension.

Unlike the Lucky Friday and Stillwater mines, the Galena Mine uses a hydraulic fill which has free (excess) water. With the addition of 10% cement, the fill obtains a strength of 2,590 kPa (375 psi) after seven days. The excess water is decanted over the top of the sand wall after the cement has settled. Fines and cement retention behind the sand wall are critical to the Galena system. If too many fines and cement are lost, the resulting fill is weak. There are two explanations for this. One hypothesis suggests that the weakness results from an excess of inter-granular space wherein the distance between particles is too great for the cement to bridge and maintain enough grain-to-grain bonds to produce adequate strength. Another possible explanation is that too much of the cement is washed over the wall and there is not enough left to develop sufficient bond strength.

Table 1. Screen analysis of backfill material.

% of Tailings Passing Screen Size

micron (mesh)

Screen Size	149 (100)	105 (140)	74 (200)	53 (270)	45 (325)	38 (400)
Lucky Friday	79	65	52	40	34	27
Stillwater	98	NA	70	62	61	NA
Galena	75	64.9	49	34	NA	28

Table 2. Backfill delivery system data.

Mine	Fill rate, t/h (stph)	Fill rate, m^3/h	Pipe diameter, cm (in)	Line velocity, m/sec (ft/sec)	Cement, %	Slurry density, % solids by
Lucky Friday	118 (130)	64 (85)	15 (6) in shaft, 10 (4) on level	0.98 (3.1) 2.4 (7.7)	8 to 9	86%
Stillwater	54 to 64 (60 to 70)	39 (51)	15 (6)	0.64 (2.1)	10 to 12	73%
Galena	73 (80)		7.6 (3)	2.3 (7.5)	10	75%

2.2 Stope Preparation

After the stope has been mined, all three mines place 0.3–0.46 m (1–1.5 ft.) of broken rock, or prep muck, on the floor of the stope. The prep muck serves two purposes. The first is to prevent the fill damage that occurs during blasting by providing a blast cushion as mining processes proceed beneath the fill. The second purpose is as a base to drive the vertically oriented DYWIDAG reinforcement bolt in to.

The mines use different strategies for installing the rock bolt-bearing plates that reinforce the backfill. At the Lucky Friday and Galena mines, the present practice is to install 15x15 cm (6x6 in) rock bolt bearing plates that have DYWIDAG nuts welded to them in a predetermined pattern on top of the prep muck. At the Stillwater Mine however, the 1.8 m (6 ft) DYWIDAG bolts are driven 15 cm (6 in) into the prep muck.

The Lucky Friday and Galena mines next lay chain link with a 5 cm (2 in) aperture on top of the prep muck and plates. At the Lucky Friday, the chain link is run lengthwise down the stope. Meanwhile, at the Galena, the chain link is run in overlapping sections from wall to wall and attached with 0.48 m (18 in) split-set bolts driven into the lowest row of split-set bolts in the stope wall (Figure 4). Then, 1.8 m (6 ft) DYWIDAG bolts are inserted through the chain link and screwed into the nut and plate below the chain link fence material. Another 15x15 cm (6x6 in) bearing plate and nut are then added to the top of the bolts and then the bolts are wired to each other and the walls to hold everything in position during backfilling. The bolts at the Stillwater Mine are placed in a pattern that is 1.2 m (4 ft) on center across the potential back and 1.8 m (6 ft) on center along the length of the stope cut. Bearing plates are then added and wire mesh is installed from wall to wall once the fill is mined under during the next stope cut.

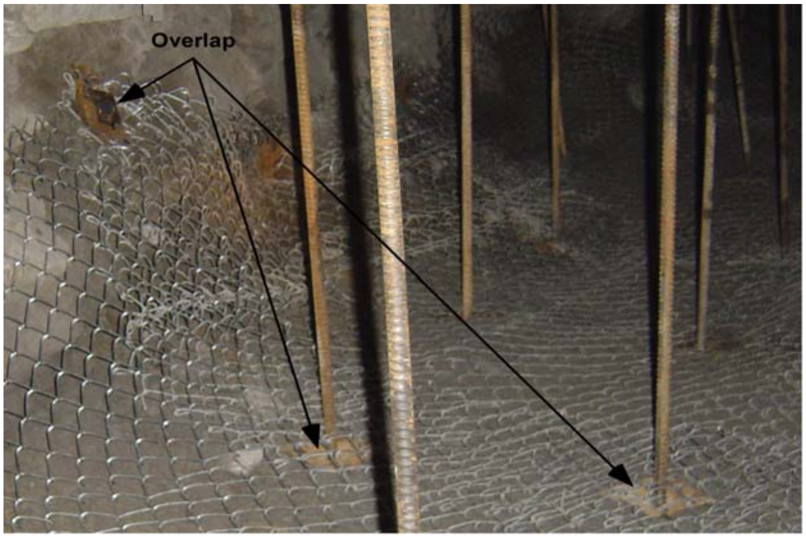

Figure 4. Installation of chain-link fence and reinforcement bolts at the Galena Mine.

To provide additional fill support in wide areas, the Lucky Friday and Galena mines place wooden stringers with 1.8 m (6 ft) bolts through them across the width of the stope. In areas wider than 3.7 m (12 ft), the Stillwater uses 15 x 7.6 cm (6 x 3 in) steel channels with bolts through them on 0.9 m (3 ft) centers. These channels are placed on 1.8 m (6 ft) centers along the length of the stope. Posts are then placed under the stringers and channels for additional support during the following cut.

All three mines construct 2.1–2.4 m (7–8 ft) high wooden dams to retain the cemented fill in the stopes (Figure 5). In an effort to save time and money, the Lucky Friday constructs dams in the access slot by pushing waste rock against the chain link stretched between the walls. Each mine places a limit on the length of stope (backfill cell) that they will fill because it is imperative to completely fill the stope at one time to prevent the formation of cold-joints in the backfill. A cold-joint is the discontinuity created when a new cemented fill is poured on top of a previous cemented fill that has started to cure. Cold-joints severely reduce the integrity of the fill and have caused backfill collapses (Figure 6).

Figure 5. Backfill retaining wall construction.

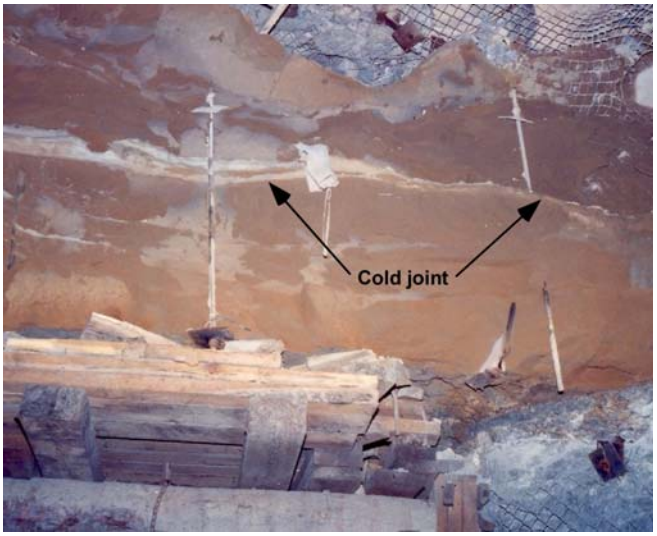

Figure 6. Cold joint in section where backfill collapsed.

At the Galena Mine, a backfill cell is typically 18 m (60 ft) long and 2.4 m (8 ft) wide. Filling a cell to 2.1 m (7 ft) of depth requires 217 t (240 st) of dry sand and 21.7 t (24 st) of cement. Assuming the current cost of cement to be approximately $95.00 per t ($105.00 per st), the cost of filling one cell is $2,520. With 435 t (480 st) of ore were mined from a cell, the additional cement cost per metric ton mined is $4.76 ($5.25 per st) for underhand mining. Including all factors, the total cost for underhand mining is $3.18/t ($3.50/st) more than overhand mining. At the Lucky Friday Mine, the rockbolting material costs in underhand mining are less because there are 10 bolts in the overhand back versus 5-6 in the underhand back. The total cost for backfilling at the Lucky Friday Mine, including the related supply costs and the labor at the stope and batch plant is $3.88/t ($4.28/st) of ore mined. However, despite higher initial costs, underhand mining is a safer and cost effective method when repair costs are considered.

2.3 Mining Practices

2.3.1 Backfill Stability

Mining cannot proceed until the backfill is sufficiently stable. Each of the mines discussed in this study uses a slightly different backfill method but with the same end-goal. The Lucky Friday Mine cures the cemented tailings for three days before mining under it. At the Galena, the next mining cut beneath the fill does not proceed for a period of three to seven days until the fill reaches a UCS of approximately 2,070 kPa (300 psi). Due to the fact that the Stillwater Mine has a much lower strength fill, samples of each backfill pour are tested for their UCS strength at three, seven, and 28 days. The Stillwater Mining Company has developed graphs that detail required equivalent compressive strength compared with stope span widths. Mining does not proceed until the testing indicates that the fill has reached sufficient strength to match the span of the stope (Jordan et al., 2004).

2.3.2 Drilling and Blasting

Drilling and blasting are the most critical processes involved in mining beneath cemented backfill. Blast holes must be drilled with the highest degree of accuracy possible. Holes drilled into the fill or even the prep muck, if loaded and blasted, could severely damage the backfill. It is standard practice to prohibit drilling closer than 0.3 m (1 ft) to the prep muck at all three mines. The Galena Mine uses jackleg drills to install blast holes in conventional underhand stopes, and in the LHD stopes, a jackleg or jumbo is used, depending on the stope width. The Lucky Friday generally drills blast holes with a jumbo while the Stillwater uses jacklegs. Over blasting a breast-up or V-cut round could also damage the fill, which would necessitate additional ground support, a very costly additional expense. Breasting up with a modified V-cut is standard at all three mines but certain situations require a burn cut to avoid damaging the backfill. At the Stillwater Mine, the first five rounds under the backfill are limited to 1.2 m (4 ft) lengths with a burn cut. This practice also results in slowing the stope advance, which gives the fill more curing time. After this, 1.2, 1.8, or 2.7 m (4, 6, or 9 ft) rounds can be taken using either a V-cut or a burn cut (Figure 7).

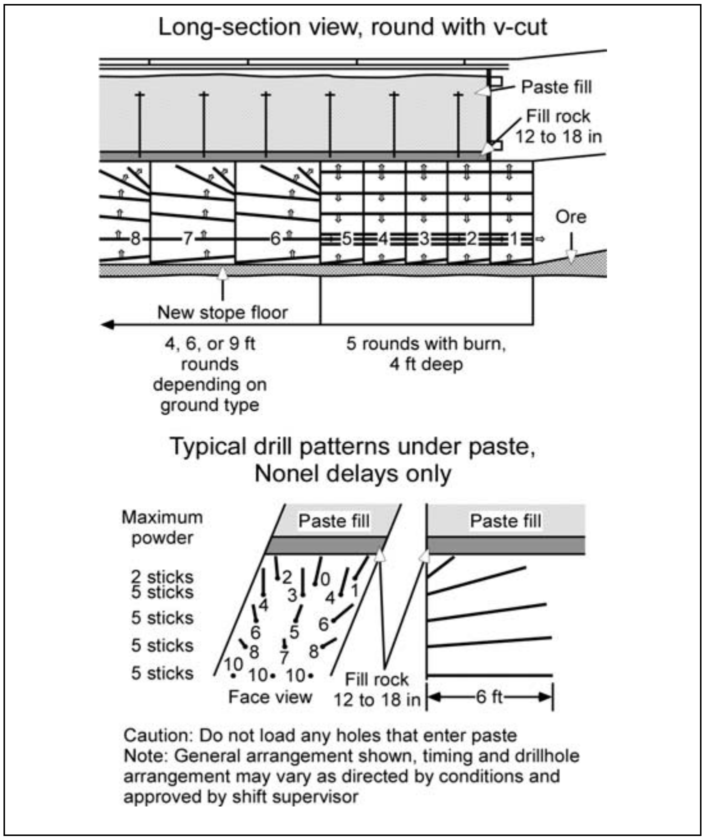

Figure 7. Drill patterns for blasting at the Stillwater Mine.

2.3.3 Mucking

Load/haul/dump units (LHDs), with capacities of 1.5 m^3 (2 yd^3), are used for muck removal at all three mines. However, the Galena Mine also uses electric or compressed air powered slushers to pull muck to the ore chute in areas where underhand mining methods are used for sill pillar recovery in conventional stopes.

2.3.4 Ground Support

The Lucky Friday and Galena mines rarely install rockbolts for ground support in the back of underhand stopes during the mining cycle. This is because the chain link material installed during the sand fill prep cycle with the vertical DYWIDAG bolts is sufficient to prevent groundfall. The Lucky Friday Mine creates additional wall support in the Gold Hunter 30 vein by installing two rows of steel mats oriented horizontally along the north wall and chain link along the weaker south wall. The mats and chain link are anchored on 0.9 m (3 ft) centers along the wall with 1.2 m (4 ft) split-set bolts and 15 x 15cm (6 x 6 in) bearing plates. On occasion, the back of the stope will be spot bolted with additional split-sets, depending on the width of the stope and the bolt pattern used in the fill prep. The Galena Mine follows a similar practice; the walls of the stope are supported by two rows of steel mats that are installed horizontally along each wall and anchored with 1.2 m (4 ft) split-set bolts on 0.9 m (3 ft) centers. However, if the crown area where the cemented fill contacts the stope walls is failing, 1.2 m (4 ft) split-sets with 30 x 46 cm (12 x 18 in) headboards are installed to provide additional support.

At the Stillwater Mine, surface support is provided to the back and walls as mining progresses under the backfill by installing 40 Kg (88 lb) expanded metal mesh with a 7.6 x 20 cm (3 x 8 in) aperture that is held in place with 1.5 m (5 ft) split-set bolts on 0.9 m (3 ft) centers. The mesh is also pinned to the back with 15x15 cm (6x6 in) bearing plates and nuts on the exposed ends of the bolts that were pre-placed in the backfill. When these nuts are tightened, an axial load is generated in the bolt between the upper and lower plates.

3.0 Geo-mechanical aspects

The safety implications related to backfill stability make it the most important aspect of underhand mining. When underhand cut and fill mining was first implemented at the Lucky Friday and Galena mines, the USBM, and later, NIOSH, installed an extensive suite of geotechnical instruments in the first pour. The object was to document how the reinforced backfill responded to the procession of mining beneath it. Backfill pressure was monitored with earth pressure cells and extensometers were used to measure stope wall closure on the backfill (Williams et al., 1990 and 1992, Whyatt et al., 1992). The data indicated that the stope walls converged immediately on the fill as mining proceeded beneath the instrument locations, inducing up to 4.2 MPa (600 psi) loads on the fill. The fill reached its ultimate strength within 1 cm (0.4 in) of wall closure and then started deforming as the walls continued to close. At the Lucky Friday and Galena mines, up to 10 cm (4 in) of wall closure was measured as the next cut was mined below it. In later tests, the vertical reinforcing bolts were instrumented with strain gages and load cells to determine the loads that were induced on them by the deforming backfill. The collected data indicate that the loads on the vertical #7 DYWIDAGs approach their 16,300 kg (36,000 lb) yield strength (Williams et al., 2000). This load results from backfill deformation caused by wall closure and the 15x15 cm (6x6 in) bearing plates at the top and bottom of the bolts resisting this deformation. A cone of compression is established between the bearing plates at the top and bottom of the bolts which induces a tensile load in the vertical bolts (Williams et al., 2001 A&B). In effect, this makes the fill a reinforced concrete beam. The fill is stable as long as the cones of compression from adjacent bolts overlap. The fill between the bolts will start to fall out due to gravity but the chain link in the back will catch it. This process is referred to as bagging. Eventually enough falls and the whole fill fails. However, the fill failure is not problematic because it occurs after the stope has advanced several cuts down (figure 8).

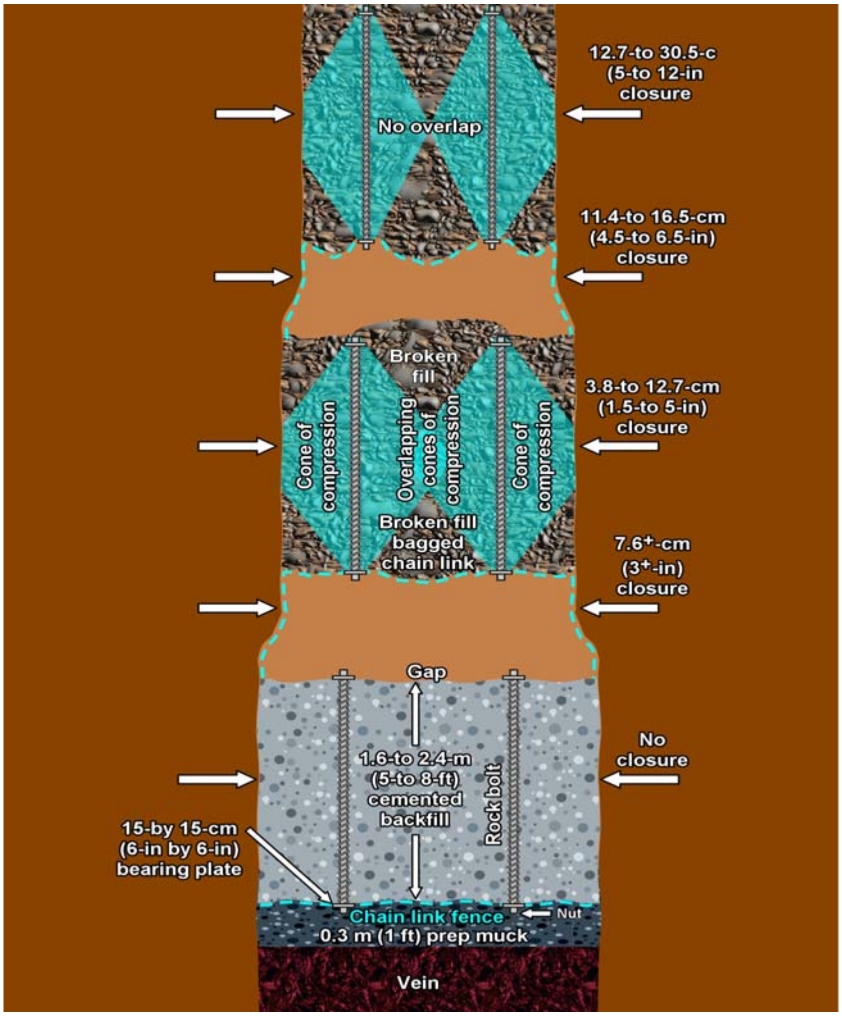

Figure 8 Geo-mechanics of underhand mining with cemented backfill.

4.0 Summary

The USBM, NIOSH, and the participating mines developed the underhand mining method as a safe alternative to the overhand mining method for rockburst-prone mines and mines with weak rock conditions. Despite major differences in their milling and backfill procedures, the Lucky Friday, Stillwater, and Galena mines have successfully implemented underhand mining methods that use cemented mill-tailings. Further, underhand mining has allowed these mines to safely mine rockburst-prone pillars and areas with extremely weak ground that could not be safely mined using other methods. Moreover, underhand mining has made it possible for the Lucky Friday and Galena mines to recover ore that was previously unrecoverable beneath the lowest levels of the mines. As such, any mine with ground control concerns should consider using underhand cut and fill mining with cemented mill tailings as a safe, cost-effective way of recovering resources from those areas.

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