Abstract

Hecla Limited is nearing completion of the Lucky Friday Mine No.4 shaft located in Mullan, ID. The shaft is collared at the 4940 level of the mine and will have a final mine level depth of 8620, or 9,590 feet below the surface. After reaching the 7400 mine level the shaft encountered ground deformation higher than allowed for in the design for a circular shaft excavation and concrete lining. This additional ground deformation required portions of the shaft concrete liner to be reinforced with frameless, steel liner plate. To eliminate the installation of the liner plate from the remaining shaft development, the design of the shaft excavation starting at the 7650 mine level was changed to an elliptical cross section based on the overall stress field orientation as well as the orientation of the structure of the host rock surrounding the shaft. The elliptical cross section was instrumented to confirm the shaft excavation and lining was performing as designed. This design change has allowed the shaft to continue to the planned 8620 mine level without the need to install liner plate in the shaft or change the overall functionality of the shaft or the Lucky Friday life of mine plan.

Introduction

Hecla’s Lucky Friday Mine is a deep, underground producer of silver, lead and zinc in the Coeur d’Alene mining district of northern Idaho (Figure 1). Primary access into the mine is via the Silver Shaft, a 5.5-m (18-ft) diameter, concrete lined shaft sunk to an original depth of 1,890-m (6,200-ft). Current production is from the Gold Hunter vein system, approximately 1,525-m (5,000-ft) northwest of the Silver Shaft.

Lucky Friday’s #4- Shaft is a 5.5-m (18-ft) finished diameter, internal shaft, or winze, being sunk to the north of the Gold Hunter vein system, from the mine’s 4760 level, 1,743-m (5,720-ft) below the surface, to the 8620 level, 2,923-m (9,590-ft) below the surface. The shaft is designed to provide access to the deep, high-grade zones of the Gold Hunter in order to increase the mine’s production and operational life. Design and engineering began in 2006, with construction starting in the fourth quarter of 2009.

Three production levels with shaft stations are planned at the mine’s 6500, 7500, and 8300 levels. Twenty-four meters (80-ft) below each production level is a skip loading pocket. Production muck will be dumped into 4.3m (14-ft) diameter bins on the production level, then fed via chutes, vibratory feeders and conveyor to skip loading flasks at the shaft.

Geology

The Gold Hunter orebody is hosted in the pre-Cambrian Wallace formation of the Belt Supergroup. The Wallace formation consists of thinly bedded argillites with a roughly east-west strike and a near vertical dip (Figure 2). These bedding/foliation planes are typically coated with talc minerals. The rock mass has an estimated rock mass uniaxial compressive strength of 48-MPa (7,000 psi) (Pakalnis, 2008), which is highly anisotropic, being distinctly weaker perpendicular to the foliation. The maximum in-situ stress strikes roughly northwest-southeast with a ratio of maximum horizontal to vertical stress of about 1.5 to 1.
Prior to excavation of #4-Shaft, it was recognized that the primary failure mode of the ground would be buckling and opening of the beds when excavating parallel to bedding. Bored raises had shown buckling of the north and south walls in the past (Figure 3).

**Figure 3: Buckling of argillite beds in north and south walls of a 1.8-m (6-ft) diameter bored raise.**

**Initial Ground Support Design and Excavation**

Preconstruction design called for 2.4-m (8-ft), 22-mm (#7) Dywidag or rebar bolts installed on 1.2-m (4-ft) centers with welded wire mesh or chain link mesh during excavation, followed by a nominal 300-mm (1-ft) thick, unreinforced, concrete liner poured in 6-m (20-ft) sections, within approximately 9-m (30-ft) of the advancing face.

The self-consolidating concrete (SCC) mix used in the shaft is supplied by a surface batch plant and delivered through a 150-mm (6-in) inside diameter borehole slickline to the mine’s 4900 level where it is loaded into transmixers and transported to #4-Shaft collar. Concrete is then loaded into buckets and lowered to the shaft forms. Sampling follows American Concrete Institute (ACI) standards, with one sample set taken for every 38 cubic meters (50-yd³) at the pour site by ACI certified technicians. Samples are cured and tested in a certified, on-site lab. The 28-day compressive strength of the SCC mix has been averaging over 50-MPa (7,400-psi).

There had been early discussions of the potential need to change the excavation shape to control the buckling of the argillite beds (Board, 2011). However, the stresses for the first 450-m (1,500 ft) were below the compressive strength of the rock, possibly due to being in the stress shadow of the mined out stopes south of the shaft, and the ground proved to be stable. Consequently, ground support was reduced to 1.8-m (6-ft) SplitSets on nominal 1.5-m (5-ft) spacing, with welded wire mesh or chain link. The concrete liner was kept within approximately 12-m (40-ft) of the bench. Virtually no ground water was encountered during sinking. As evidence of the lack of time-dependent deformations, the shaft remained stable for 16-months of inactivity, December, 2011, through March, 2013, while the mine’s Silver Shaft was rehabilitated.

**Shaft Liner Issues Appear**

The 6500 shaft station, 2,274-m (7,460-ft) below the ground surface, was cut in early January, 2014, without incident, although bowing of the hanging rods between the brow and the sill was noted as the shaft was sunk below the level. The first report of cracking in the liner was made on January 31, with report of a large horizontal crack running horizontally around the liner 1.8-m (6-ft) above the brow. A vertical crack with 6-mm (¼-in) offset appeared in the north wall at the same elevation in early February, with spalling and breakout to a hanging rod reported soon after.

Believing this fracturing to be caused by opening and buckling of the argillite beds as had been seen in the bored raises, shaft ground support was increased to include cable bolting prior to placing concrete. Grouted, 18-mm (0.7-in), bulbed cables, with 6-m (20-ft) minimum embedment were placed in rows spaced 1.5-m (5-ft) apart vertically. Each row consisted of five cables in the north wall and five cables in the south, spaced 1.2-m (4-ft) apart horizontally, to provide deep anchorage and restraint to bedding separation. This bolting pattern was continued until the shaft was 12-m (40-ft) below the 6580 loading pocket. No difficulties with ground control were noted between the cessation of cable bolting below the 6580 and the approach to the 7500 level.

Cable bolting resumed as the shaft bottom came within 12-m (40-ft) of the 7500 production level, (Figure 4), approximately 2,580-m (8,460-ft) below the ground surface, on July 22, 2014. The concrete liner was completed to the brow of the 7500 shaft station in early August of that year, and excavation of the level began. By October 28th, the shaft had reached the brow of the 7580 level, and severe, vertical fracturing of the north wall of the concrete liner above the 7500 brow developed. Shaft ground support was increased to five 6-m (20-ft) cable bolts per row on the north and south walls spaced on a 1.2m x 1.2m (4ft x 4ft) pattern, with 3.6-m (12-ft) Dywidags placed midway, or “five spotted”, between them (Figure 5).
Cracking of the shaft liner between the 7500 and 7580 levels began in early November with some simple flaking and spalling at set 132, approximately midway between the two levels. At that time, the decision was made to install shaft instrumentation to monitor rock mass radial deformations as well as tangential and radial stresses induced in the concrete liner. A study also began on alternative shaft excavation shapes to improve stability. Damage to the existing concrete liner continued and expanded, ultimately stretching from 30-m (100-ft) above the 7500 level to 12-m (40-ft) below the 7580 level, an extent of nearly 75 meters (245-ft). This area eventually required installation of steel liner plate for reinforcement and, in some areas, actual demolition and replacement of concrete.

**Change in Shaft Excavation Shape**

Traditionally, timbered shafts in the district were mined with “the long horizontal axis oriented normal to the bedding of the country rock. Experience has shown that such a position is best able to resist rock pressure at depth” (McWilliams, 1960). After consideration, it was decided to change the excavation to a more elliptical shape with the long axis perpendicular to bedding, similar to the orientation of a timbered shaft, believing this would provide a more stable opening and reduce point loads on the concrete shaft lining. To examine the impact of such a non-circular shape, some simple numerical simulations of both circular and notched shaft cross sections were run in UDEC, a “discontinuum” type program developed by Itasca Consulting Group. The models simulated a series of thinly-spaced beds oriented east-west, with the major principal stress oriented N40W and assumed to be 1.5 times the vertical (gravity) stress, or about 100-MPa (14,500-psi) (Figures 6 and 7).
The simulation, as expected, showed the bedding tends to slip and buckle at the north and south sides of the shaft where the beds are more-or-less tangent to the wall in the circular case (Figure 8). The results showed an elliptical-shaped movement zone that is about 1.8-m (6-ft) deep on the north and south sides of the shaft (Figure 9). The maximum movement was shown to be directly perpendicular to bedding at opposite sides of the shaft.

Figures 10 and 11 show the notch shape largely eliminates the buckling and shaft deformation. The only significant movement remaining was shear on bedding directly at the notch tip.
Based on this modeling, the decision was made to change the excavated cross section of the shaft to an elliptical shape, long axis perpendicular to bedding, with the final dimensions determined by the capabilities of the equipment being used to mine the shaft (Figures 12 and 13).

Instrumentation

The change to the elliptical cross section was made at set 138, approximately 25-m (80-ft) below the 7580 level, or 2,630-m (8,628-ft) below ground surface. Pressure cells and extensometers were installed at set 140, 2,640-m (8,668-ft) below surface, to better understand the magnitude and orientation of deformations, the time dependency of the displacements, and the load distribution in the liner.

Three 10-m (33 ft) multipoint borehole extensometers, Smart MPBX’s, produced by Mine Design Technologies of Kingston, Ontario, were installed in 50-mm (2-in) boreholes, one each in the north, west, and south shaft walls. Four radial, concrete pressure cells, model 4850-2, and two tangential stress cells, model 4850-1, by Geokon of Lebanon, New Hampshire, were installed at the same elevation. The tangential cells were installed in the north and south shaft wall positions where they were expected to see the highest stresses (Figures 14 and 15).
The pressure cells and extensometers were installed during the shaft liner concrete pour on June 4, 2015, while the area had been excavated on May 30. Therefore, the shaft bottom had advanced 6.6-m (21.5-ft) and the shaft walls had five days to equilibrate prior to installation of the instruments and pouring of the concrete liner. Prior to being destroyed on June 27, extensometer #46 in the north wall of the shaft showed the bedding was moving at least 3-m (10-ft) from the shaft wall, deeper than what was predicted by the model (Figure 16). The anchor at the collar showed a maximum displacement of 14-mm (0.55-in), while the anchor one meter in from the collar showed a displacement of 22.6-mm (0.9-inch). This differential can most likely be attributed to the dilation of the bedding near the shaft wall immediately after excavation. As soon as the concrete was placed and began to strengthen, the movement of the collar was arrested, while the dilated beds behind the collar continued to move, compressing any open space between the beds. This north wall extensometer showed the greatest displacement of the three installed. Extensometer #47 in the west wall of the excavation showed maximum displacement of only 1.3-mm (1/16-in), while extensometer #45 in the south wall showed 18.3-mm (3/4-in).

The maximum pressure (compression) in the liner was 10.9-MPa (1,580-psi) recorded on October 11, 2015, at the north end of the elliptical excavation, in tangential pressure cell T1 (Figure 17). The rate of increase diminished as the concrete liner cured and shaft excavation moved away from the area. The highest compressive pressure seen by a radial cell was in the east wall where, other than a few spikes caused by instrument sensitivity to temperature fluctuations, the pressure reached 6.5-MPa (940-psi) (Figure 18).
Conclusions

Over 200-m (655-ft) of shaft have been mined using the elliptical cross section, with no evidence of cracking or other damage to the concrete liner. Pressures and deformations seen in the instrumentation at set 140, 2,640-m (8,668-ft) below surface, have not exceeded the liner strength. The 8300 production level, more than 2,830-m (9,280-ft) below the ground surface, is currently being mined with no evident damage to the shaft liner. Further instrumentation will be needed to confirm the performance of the elliptical excavation between the 8300 and 8380 shaft stations, where the liner will be subjected to conditions similar to those that caused deformation and fracturing of the liner between the 7500 and 7580 levels.

The elliptical cross section requires an additional 15% in excavation, 11% additional ground support, plus an equivalent 15% of concrete. Review showed that the potential elimination of concrete repair work and steel liner plate installation would more than compensate for the additional excavation, support, and concrete. We believe the change will also ensure the completion of the shaft to the designed shaft bottom at the 8620 level, 2,923-m (9,591-ft) below the surface.

References