Ground Control Design Challenges at the El Boleo Copper Project

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ABSTRACT

The El Boleo Copper Project is currently in the final design stages for development of a 3-MM-tonne/yr underground copper mine located in Baja California, Mexico. The nearly horizontal mineralized zones are amenable to exploitation by conventional mechanized coal mining technology using continuous miners, shuttle cars, and belt haulage. The mine design resembles a typical full-extraction coal mining operation utilizing a sequence of mains, sub-mains and production panels. Due to numerous faults, mining will be conducted as several small adjacent mines accessed through adits from large arroyos cutting through the mine area. Up to four seams may be mined in some areas with a maximum overburden depth of about 250 m. The ore zone is relatively weak and plastic, subject to extensive creep over time. The mine workings will pass through areas of historical shortwall mining panels where the ground has flowed into old entries and gob areas, and then reconsolidated. A small test mine was developed to evaluate mechanical cutting performance, roof-bolt anchorage capacities, roof and pillar stability and caving behavior. In-mine measurements were combined with two- and three-dimensional FLAC models to evaluate alternative development and production pillar designs. The paper will discuss the various factors influencing ground stability at the El Boleo project and the strategies employed in developing a suitable ground control design.

INTRODUCTION AND BACKGROUND

The Boleo District is located near the coastal town of Santa Rosalía in Baja California Sur, Mexico, about midway along the peninsula. In 1868, copper nodules or concretions known as boleos were discovered in a dry riverbed and soon after, high-grade (plus 20%) copper ore was being surface mined and shipped to Europe for treatment. Eventually, mining moved underground, grades dropped, and a smelter was constructed in Santa Rosalia with production continuing sporadically until 1985. The climate is typical of the arid Sonoran desert region with sparse vegetation and minimal seasonal precipitation.

The Boleo deposits occur within a Miocene rift zone basin and consist of a succession of fine to coarse clastic sedimentary rocks characterized by a number of coarsening upward cycles of deltaic deposited sediments. Faulting is common throughout the district. The dominant faults are steeply dipping normal faults striking northwest and downthrown to the west by up to 200 meters (m). These offsets, combined with the easterly dip of the mantos, yield a stepwise configuration of the mineralized beds. Major faults are typically separated horizontally by several hundreds of meters, although lesser faults are common and are more closely spaced. The extensive faulting, with vertical offsets ranging from less than a meter to tens of meters, divides the project area into relatively small, irregularly-shaped blocks. The ground immediately adjacent to fault zones is generally observed to be degraded, with little or no structural strength. The surface topography is highly variable and consists of flat-topped mesa structures that are deeply incised by rugged, steep-sided arroyos. The depth of cover varies from zero to several hundred meters.

Copper-cobalt-zinc mineralization occurs throughout the Boleo District within clay-rich horizons or beds known as “mantos.” The mantos correspond to the lower units of similar stratigraphic sequences occurring in a repeated series. Each sequence consists of a general coarsening of the sediments from the base to the top. The ore-bearing mantos are the lowest beds in each sequence and consist of a 1-m-thick basal laminated mud horizon overlain by mineralized slump breccias up to 20 m thick. The ore zones are overlain by progressively coarser material of tuffaceous claystone, siltstone, sandstone, pebbly sandstone, and eventually cobble- to boulder-sized conglomerates. A simplified lithologic section is shown in Figure 1. The contact between the mantos and floor rocks is sharp; however, the contact with the roof rocks is more gradational. Mineralization is finely disseminated in the breccias with the richest material occurring in the laminated basal section of the mantos. The Boleo District has been extensively mined by underground methods for nearly a century, and much of this early mining extracted only the very high-grade material within the basal part of the manto and backfilled the stopes with the lower grade breccias, containing copper grades of 1% to 2%, or more.

Seven mantos are present, but most production to date (83%) has been from Manto 3. Underground mineable reserves have been identified in four mantos, although the reserve areas only partially overlap. Current mining plans involve exploiting intact areas that have never been mined and mining through previously mined areas to recover intact mineralized rock in the roof and pillars, and ore-bearing rock used as backfill in old stopes.

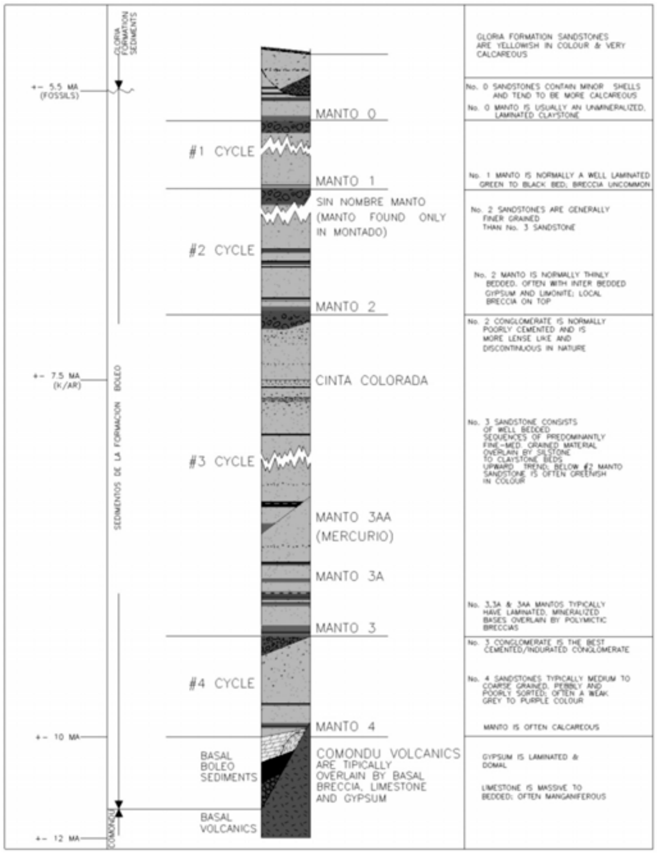

Figure 1. Lithologic Section of Manto Structure.

GEOTECHNICAL INVESTIGATION

Commercial feasibility for underground mining of the Boleo deposit requires favorable ground behavior in response to high-production, high-recovery mining methods similar to those used in the coal mining industry. The primary objective of the investigation was to assess the geotechnical feasibility of underground mining the Boleo reserves and involved the following tasks: (1) review of existing data, (2) inspect historical mine workings, (3) conduct geotechnical monitoring in the Test Mine, and (4) determine laboratory physical properties of recent core samples.

Review of Existing Data

A large portion of the project area has been previously mined. Many single drifts are present; however, the most prevalent mining method evolved into a modified type of shortwalling, in which the miners loosened the high-grade manto with picks and shoveled it onto a conveyor that extended across the face. The overlying lower-grade breccia was excavated and placed behind the conveyor as backfill. Timber posts were set for support as the faces were advanced. Historic descriptions of this mining method indicate the abutment loading of the shortwall face caused the face to yield up to 100 m ahead of the face (Wilson 1955). This yielding was often severe, causing the entries adjacent to the unmined panel to converge sufficiently to be unusable. It was theorized that the pillars yielded readily during mining, minimizing stress concentrations and allowing a regional subsidence to take place, where the flexible roof overburden "sat down" on the backfill and yielded pillars without causing catastrophic damage to the immediate roof.

The Apolo access drift, re-mined in 1970 through some old backfilled shortwall stopes, was recently rehabilitated for inspection. The 2.2-m-wide drift was supported with timber sets and had remained stable and intact. A previous test area was excavated 4.5 m wide through a shortwall/backfill area and supported with roof bolts and steel beams. The area was still stable and examination of the old stopes showed that settlement of the roof over time had compressed the backfill to such an extent that it was difficult to distinguish between *in situ* pillars and compacted backfill.

Geotechnical Monitoring and Observations in the Test Mine

The primary geotechnical evaluation for underground mining was based on a test mining program conducted on the Boleo property at the Texcoco Test Mine (Agapito 2006). The Test Mine, shown in Figure 2, consisted of an adit and five side drifts (crosscuts) that were developed to demonstrate the feasibility of development mining and pillar extraction. The furthest crosscut from the portal was used for geotechnical monitoring only. The other four crosscuts were pillared crosscuts, mined sequentially toward the portal. The mine was developed in Manto 3 and was driven partially through old workings. To document the ground behavior at the Test Mine from mining, several geotechnical monitoring stations were installed. The monitoring stations were installed immediately after mining and consisted of two- and three-position wire extensometers (telltales) and floor pins. The telltale anchors were installed at depths of 1.8, 4 and 6 m above the roof anchor. Figure 3 shows a typical installation of a three-position telltale. The floor pins were installed adjacent to the telltales in holes 75 millimeters (mm) below floor level, for protection.

The telltales provided a history of roof movements, between each of the telltale's anchoring horizons and the mine roof horizon. Significant, but non-critical movements were documented at every telltale location. Measurements between roof bolts and the floor pins showed significant convergence during and after test mining. However, elevation surveys of the floor pins showed no significant floor movement and only minimal horizontal deformations of the floor pins, averaging less than 20 mm.

The primary roof support was untensioned, fully resin-grouted, 2.1-m-long, 22-mm-diameter rebar roof bolts installed in 33-mm-diameter drilled holes. Rows of four roof bolts with plates were installed on 1-m spacing rows through steel straps and wire mesh. Pull tests were conducted on specially installed bolts at different locations. Yielding occurred at the resin-rock interface at pulling forces between 12 and 20 short tons.

The composition of the immediate roof varied and included clay mantos, breccias, and sandstones. The roof span also varied but was generally less than 4.5 m. During development, the roof was competent and remained intact until permanent roof support was installed. Where faults were encountered, and when mining through historical mine workings, the immediate roof rock was fractured and portions of the roof caved before permanent roof supports could be installed.

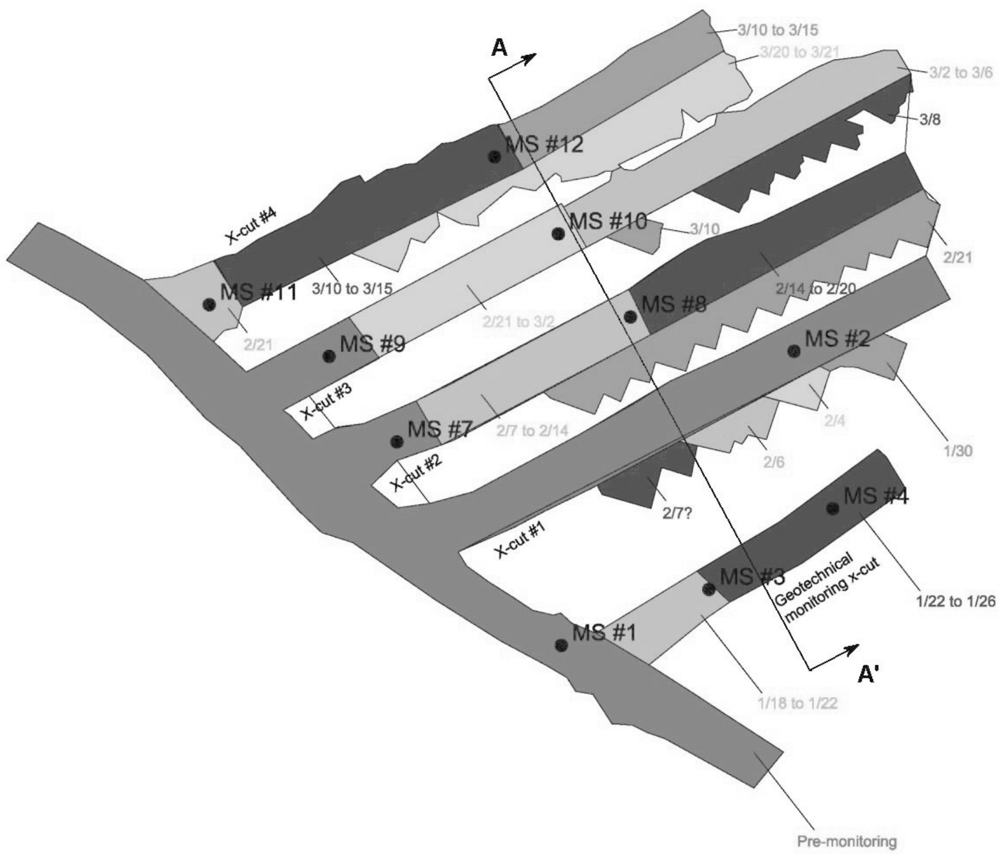

Figure 2. Test Mine Layout in Pillaring Area.

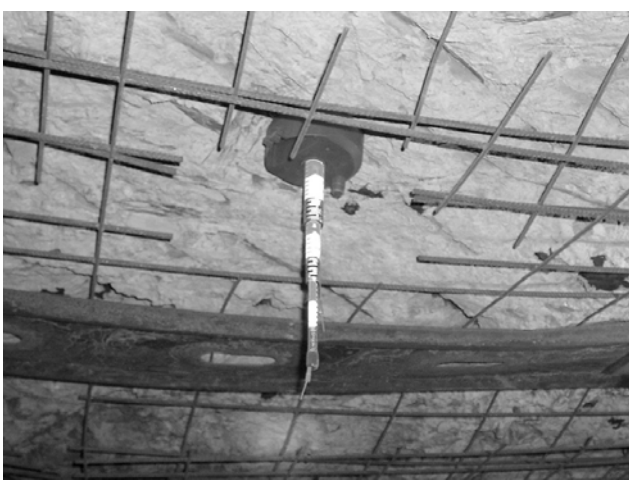

Figure 3. Three-Position Telltale Installation.

Various types of standing support were utilized including timbers, timber cribs, and steel beams supported by timbers or steel legs. Timbers were set on 1-m spacing along most of the rib lines to control rib sloughage. Many of these timbers bowed and broke as a consequence of the significant pillar yielding that occurred during mining (Figure 4). A few timber cribs were built to support the roof in some historical single-entry mine openings and functioned well, with no reported failures. Steel beams were installed in some locations and were set on either wood timbers or steel legs. Many of the legs did not perform well. The legs were set on the hard conglomerate floor and as the mine opening converged, a significant number of the legs failed and the beam ends crushed (Figure 5).

During pillaring experiments, the immediate roof initially collapsed to approximately 2.5 m above the original immediate roof horizon, generally within hours or days after mining. None of the immediate roof caving progressed out of the pillared area and stopped where the opening narrowed to the initial 4.5 m width. This indicates that the critical opening width for which cascading roof failure is likely to occur is greater than 4.5 m and pillared area caving will likely be confined within the pillared area.

The main roof did not cave during pillar extraction mining; however, surface cracks, attributable to mining induced subsidence, and most likely a consequence of the main roof caving, were documented about 5 weeks after mining. The delay of the main roof caving is likely due to the low recovery ratio and small dimensions of the test mining area. The eventual caving of the main roof prior to any significant closure of the access drifts was a good indication that successful pillaring of larger districts with higher recoveries should be possible.

Figure 4. Timber Posts Broken By Pillar Convergence.

Figure 5. Crushed Steel Beam Resting on Timber Support.

The pillars of the Test Mine were comprised primarily of clay manto and breccias; however, some sandstones and conglomerates were also present. The sandstone and conglomerate portions of the pillars remained stable during development and pillar mining, whereas the clays and breccias deformed plastically. Once mined and subjected to abutment stresses, the pillars gradually "squeezed" and "flowed" into the excavated openings (Figure 6). Pillar convergence data indicated an average pillar convergence rate of 2 mm per day over the 60-day monitoring period. Because this represents time-dependent plastic yielding, it is doubtful a reasonably sized pillar would fail catastrophically; however, the resulting loss of opening clearance (both vertical and horizontal) and rib stability over time could be problematic to operations if no additional measures are implemented.

The sandstones and conglomerates provided relatively stable ribs; however, the clays and the breccias degraded and failed, sloughing into excavated openings in many locations as a consequence of pillar convergence and loss of moisture from exposure to air. The incidence of failure increased with mining height and time since initial mining. At the completion of test mining, almost all of the ribs were experiencing some degree of disintegration, and timbers and lagging were being used to minimize the amount of rib material that sloughed into the opening.

Figure 6. Plastic Deformation of Manto into the Mine Opening.

Physical Property Testing

A number of samples were collected from surface and underground core drilling and tested in the laboratory to determine the strength and elastic properties of the various rocks present in the mining area. A total of 97 unconfined compressive strength-Young's modulus tests and 34 Brazilian tensile strength tests were performed as well as a few slake durability and point load tests. The test results indicated that Manto 1 and its surrounding ground are similar but slightly stronger than Manto 3, while Manto 2 and Manto 4 are significantly weaker. For the purposes of modeling and mine design, the properties of Manto 1 and Manto 3 were assumed to be equivalent and Manto 2 and Manto 4 were considered equal, but weaker than Manto 3.

NUMERICAL MODELING ANALYSIS

The numerical modeling analysis was conducted using the Itasca FLAC modeling software. Both the two-dimensional (FLAC 2D) and three-dimensional (FLAC 3D) packages were employed. Initially, a 2D model of the Test Mine was calibrated by adjusting the physical property input values such that the modeled ground response agreed with the ground movements measured during mining. Once calibrated, alternative production panel designs were modeled in 3D to evaluate the stability of the various underground structures (pillars, openings) over the expected life of each structure. Guidelines were developed for each manto to specify appropriate pillar dimensions for different mining areas, based on cover depth and rock type.

The numerical models utilize physical properties corresponding to the rock mass behavior, which is generally significantly weaker than the behavior of the small samples tested in the laboratory. An initial estimate of the rock mass strength was conducted using the Hoek-Brown failure criterion. Laboratory rock strengths and measurements of fracture (joint) properties were used to determine the Geological Strength Index (GSI) and the parameters describing the failure curve. From these, rock mass values for cohesion and angle of internal friction were calculated for all rock types.

Model Calibration

The calibration model was a 2D vertical section aligned perpendicular to the pillaring crosscuts as shown in Figure 2. The first model run used the rock mass properties obtained from the Hoek-Brown method, as described above, for Manto 3. The soft manto material exhibits significant non-linear behavior and was modeled using both strain-softening plastic and viscoelastic characteristics. The plastic component is an inelastic deformation under a constantly reduced, residual load estimated as the average material strength minus one standard deviation. The viscoelastic, or creep component, is a time-dependent deformation that may relieve stress and provide a variable load resistance, dependent on the strain rate. Typically, the magnitudes of the deformations corresponding to the plastic and viscoelastic components are approximately equal.

The differences between the modeled output displacements and the actual measurements were used to adjust the various input properties (geologic strength index [GSI], compressive strength, etc.) over four iterations until the model results provided a suitably close agreement with the field measurements. The maximum modeled roof-to-floor closure is about 300 mm, which compares well with the maximum measured ground movement of 430 mm.

Modeling Strategy

The currently proposed overall extraction plan consists of sequencing a number of relatively independent sections located between faults. The sections are accessed by adits driven from the arroyos and the ore is developed through a system of sub-mains and pillar extraction panels. Chain pillars and barrier pillars will be extracted during retreat. Figure 7 shows the plan-view layout of a typical panel area and the associated main and sub-main entry systems. Because of the vertical geometry component associated with caving in the production panels, the FLAC 3D modeling program was selected to analyze the production mine plan. The bold rectangle in Figure 7 indicates the area modeled and Figure 8 shows a 3D view, including caved areas and overburden. Retreat mining was simulated by multiple cuts in which the manto material was removed and replaced with gob material, then cycled to equilibrium before the next cut.

An initial base model was developed based on empirical design methods and the calibrated rock properties. A series of about 15 models were then run to compare pillar and entry stabilities for different pillar widths at different cover depths and mining heights. Separate series of models were developed for Mantos 1 and 3 and for Mantos 2 and 4 owing to the different material strengths.

Because the rocks are relatively weak and subject to non-linear plastic deformation, the models showed a “failed” or “yielded” state, even for conservative models that would be categorized as stable. To account for this yielding behavior, evaluation of the stability of the individual models was based on the magnitude of entry closure. As pillar loads increase (smaller pillars or deeper cover), the vertical closure also gradually increases until a failure point is reached and the closure significantly increases. These high

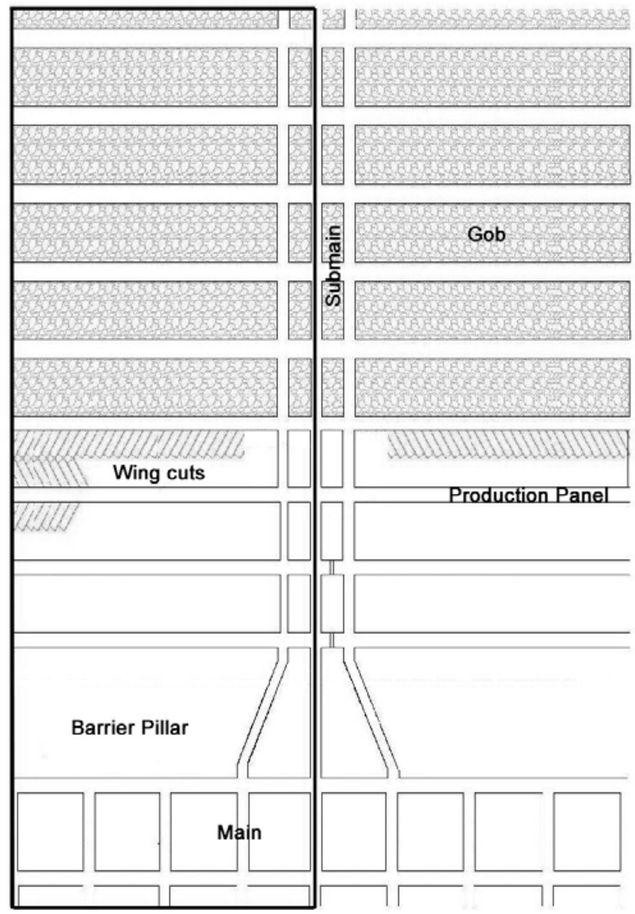

Figure 7. Layout of Production Pillar Extraction Panels.

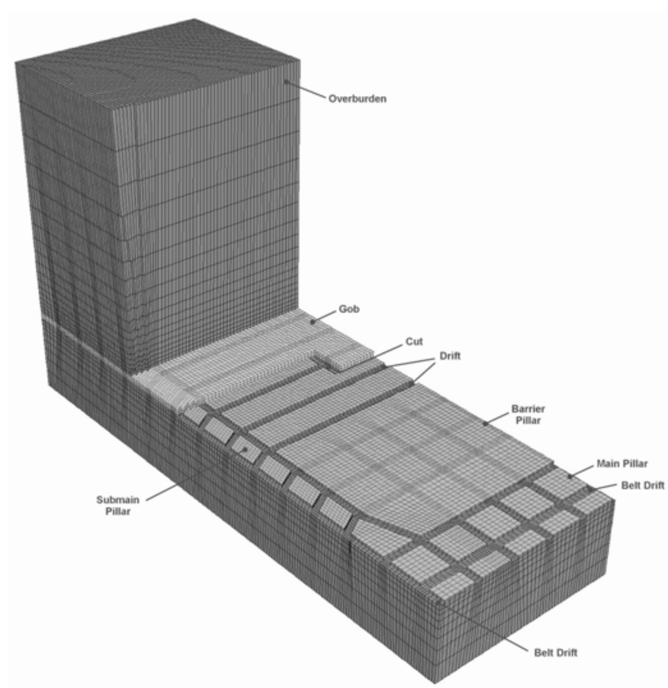

Figure 8. Three-Dimensional View of the Modeled Panel Structures.

closure rates are an indication of instability. Therefore, comparisons between the different modeling cases were based on the total convergence adjacent to the final production panel over the 112-day expected life of the sub-main and included both plastic and viscoelastic deformations.

Modeling Results

The model results show relatively low loads on the barrier pillar, corresponding to the weight of the overburden. The pillar edges and all of the sub-main pillars also show low loads as a consequence of yielding. As the production panels are retreated, a small amount of additional yielding of the sub-main pillars and load transfer to outby pillars is noted; however, the additional loading is minor. Figure 9 shows a typical stress distribution during pillar extraction operations.

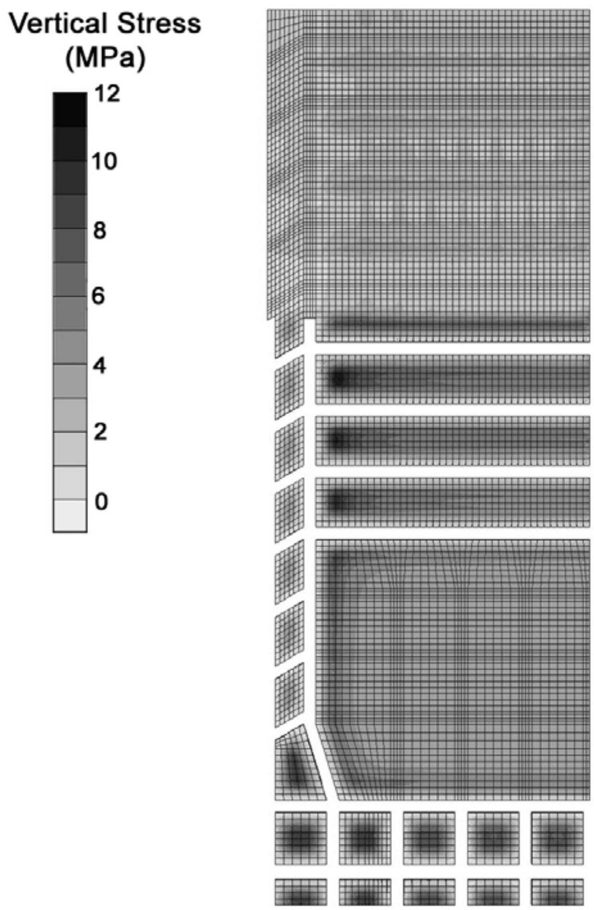

Figure 9. Vertical Stress Distribution During Pillar Extraction.

The closure value used as the pillar/drift failure criteria was derived from the Test Mine convergence data. As discussed above, convergence in the test mine at several monitoring locations exceeded 400 mm. At this magnitude of convergence, the drifts remained open, and after inspection, were deemed safe to work in. No catastrophic pillar or entry failures were observed. For purposes of the modeling comparisons, the pillar/drift failure criterion was defined as entry convergence exceeding 340 mm, based on equipment clearance considerations.

<u>Manto 3 and Manto 1 Results</u>

For Manto 3 and Manto 1, modeled convergence generally increased linearly, with cover depth, up to the maximum expected depth of 230 m. The models evaluated both 10- by 20-m and 20- by 20-m sub-main pillar sizes at depths of 100, 165, 200 and 230 m. Panel length also affects the total closure, but only slightly, through additional time-dependent (creep) deformations. Figure 10 shows the calculated entry closure for the two pillar sizes. Total entry closure and closure rate at the sub-mains comparison point were greater for the 10-m cases than for the 20-m designs. At 200 m depth, the total closure is approaching the 340-mm allowable limit and the 10-m pillars are considered marginally stable. The lower closure rate of the 20-m pillars provides a margin of safety against exceeding the closure limit. Based on the modeling results, the 10-m-wide sub-main pillar was considered adequate for cover depths of up to at least 200 m. For depths over 200 m, a 20-m-wide sub-main pillar was recommended.

Five models were run to evaluate the stability for configurations using mining heights of 3 and 4 m. The 3-m model is similar to the 2-m base case at a depth of 100 m; however, convergence for the 3-m model is more than two times greater than for the base case at 200-m depth. Larger convergence is expected for the 3-m cases and the calculated value at 200-m depth is not an extreme increase, such as shown by the definite-failure cases. However, the 3-m high configuration is considered only marginally stable at 200-m depth, and the relatively large convergence may present operational problems. It was recommended that all development mining be restricted to a maximum height of 2 m, taken at the top of the intended mining horizon with the remainder of the thickness removed from the floor during retreat. The 4-m models showed excessive convergence even at 100 m, and the proposed mine design is not considered stable for a 4-m mining height at any cover depth.

<u>Manto 2 and Manto 4 Results</u>

Models using the Manto 2 and Manto 4 properties were evaluated at depths of 100, 165, 200 and 230 m. Based on the 340-mm allowable closure limit, the 10-m sub-main pillar width was found to be adequate for up to 130 m depth and 20-m pillars were adequate for up to approximately 180 m depth (Figure 11). All models showed excessive convergence above 180 m depth. However, with no actual mining experience for Manto 2 and Manto 4 models calibration, the model predictions could vary significantly from the actual ground reaction to mining. It is believed that Manto 2 and Manto 4 can be successfully mined; however, the exact cover depth at which the 20-m pillars become inadequate or what size pillars will be required at maximum overburden depths will have to be determined after there is some operational experience mining these mantos.

SUMMARY AND CONCLUSIONS

Overall, the geotechnical investigation did not identify any conditions that would preclude mining the remaining Boleo resource using the proposed pillar extraction mining method. Many unknowns at the start of the project were answered during the test mining phase and a number of geotechnical conditions were identified that will require attention during mining. Measurements made during the test mining enabled development of calibrated

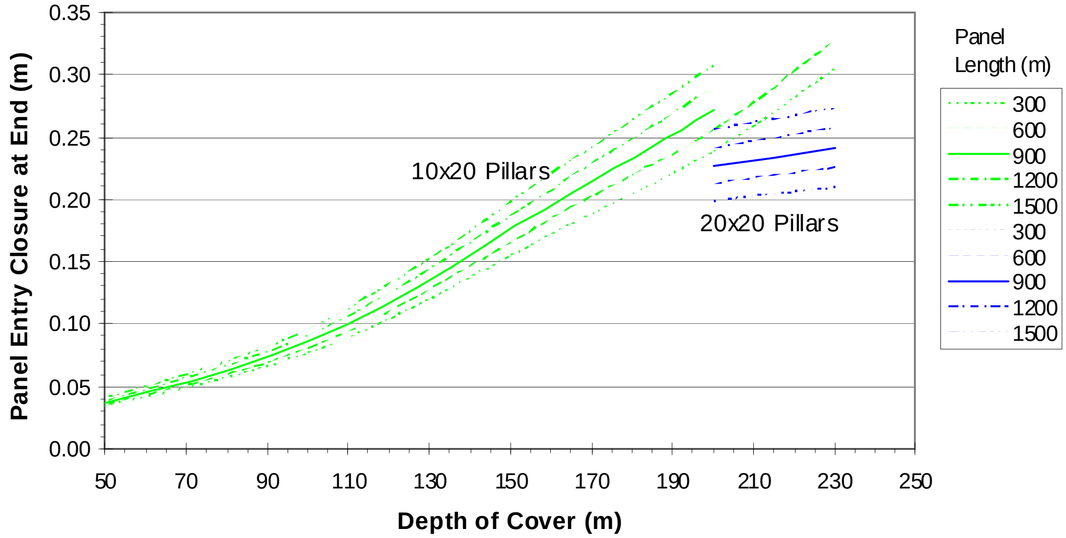

Figure 10. Entry Closure for 10- and 20-m Pillars in Mantos 1 and 3.

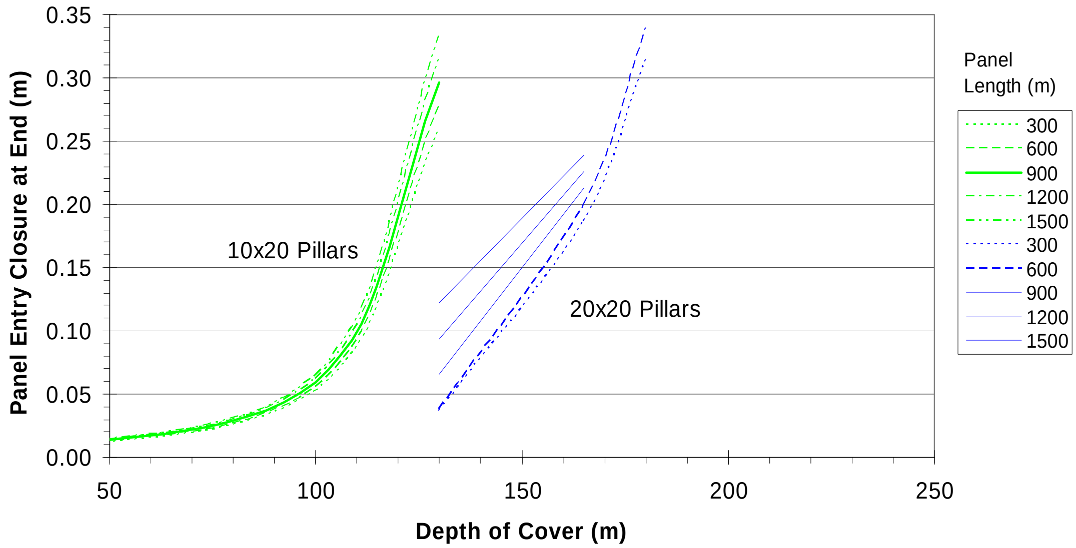

Figure 11. Entry Closure for 10- and 20-m Pillars in Mantos 2 and 4.

numerical models, increasing confidence in the accuracy of the ground behavior predicted by the models. Some specific conclusions and recommendations developed during the investigation include the following:

- Additional roof support may be required when crossing fault zones. Fault crossings should be avoided, when possible, in pillar extraction panels. To minimize the risk of premature roof caving, pillars directly under the fault should be left-in-place until such time as a safe extraction plan is developed.

- Difficult ground conditions may occur between unmined areas and caved shortwall stopes. These transition zones are expected to have ground conditions similar to small faults and may require additional ground support. As with faults, pillars directly under the broken ground should be left-in-place during pillar extraction until safe extraction plans are developed.

- Based on roof conditions and pull-test results, 19-mm- or 16-mm-diameter roof bolts might perform as well as the tested 22-mm roof bolts. Additionally, the bolt length might be reduced to 1.8 m without sacrificing roof stability.

- The use of steel beams was recommended only where the roof is broken and roof bolts are ineffective. All support legs and other standing supports should incorporate yielding mechanisms to avoid support damage as the opening converges.

- Rib support will be required in many locations; however, use of timbers is problematic. A possible solution is the use of fiberglass bolts and plates, provided that they are compatible with the ore beneficiation process. To contain sloughage, mesh could be installed beneath bolts or behind standing supports.

- Reasonable roof caving behavior was exhibited during pillar extraction tests. The roof did not cave uncontrollably during development and did not hang up for an extended period of time. The critical opening width is expected to be greater than 4.5 m.

- Monitoring of pillar stresses was ineffective in assessing stability. A better measure was the entry closure rate from which accelerating movements (impending failure) and excessive movement (clearance problems) could be determined.

- The 10- and 20-m pillar width alternatives appear feasible for Mantos 1 and 3 up to the maximum cover depths. Preliminary depth limits were developed for Mantos 2 and 4; however, additional data and modeling are required to confirm adequate pillar sizes.

- Mining heights of 2 m are feasible throughout the project area and heights of 3 m are acceptable for short-term conditions. Thick seams should be mined to 2 m initially and increased to full height only during retreat. Mining should not be attempted at heights of 4 m, or more.

REFERENCES

Agapito Associates, Inc. (2006) “Preliminary Geotechnical Performance Study for Underground Mining of the El Boleo Copper Cobalt Project,” Baja Mining Corp. technical report files, 73 pages (used by permission).

Wilson, I. F. (1955), “Geology and Mineral Deposits of the Boleo Copper District, Baja California, Mexico,” Geological Survey Professional Paper 273.