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Recent Technological Innovation for the New Generation of CRIST Sensors—A Practical Approach in China's Largest Underground Nonferrous Mine

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Abstract

Located in Shangri-La county, Yunnan Province, China's biggest underground nonferrous mine Pulang Copper Mine is under construction. To date, the defined copper reserves at the Pulang Copper Mine are 4.8 million tonnes of copper and an average grade of 0.34%. The mineralized zone is 2300 m long, 600 - 800 m wide, and 1000 m high in a dome shape. The first-stage mining and processing capacity is 12.5 million tonnes of ore per year. By geotechnical investigation, ore haulage is adopted via a drift and ore pass development system. From mineralogical analysis, a majority of the Pulang copper ore body is classified as a type III rock, which is generally considered to be suitable for block-caving methods. As an update to the traditional mine-to-mill approach, a cave-to-mill integrated production concept is then introduced. This is essentially the integration of underground mine production scheduling and monitoring with surface mineral processing management based on fragment size and geometallurgical ore characteristics. Several unique challenges experienced during the project design and construction, as well as a number of features aimed at mitigating these problems, are also discussed in this paper.

Keywords

Block Caving, Cave to Mill, Geometallurgy, Lithology Sensors

1. Introduction

Located in the far north of Shangri-La County, Yunnan Province, Pulang Copper Mine is the largest underground nonferrous mine being under construction in China. Discovered in 2001, the defined copper reserves in the Pulang Copper Mine are 4.8 million tonnes of copper with an average grade of 0.34%, in addition to ca.145 tonnes of gold, 2754 tonnes of silver, 0.19 million tonnes of molybdenum, and 10.5 million tonnes of sulfur. Based on numerous mining and geotechnical preliminary studies and ore body modeling datamine by ENFI, this paper described the main research design [1] [2]. There are four stages in the construction of this mine in which the first-stage mining and processing capacity is aimed at 12.5 million tonnes of ore per year. When it ramps up to this target production rate, the mine will produce a concentrate containing 50,000 tonnes of copper and 968 tonnes of molybdenum. A drift and ore pass system is designed for ore haulage with a block-caving mining method. Semi-autogenous grinding and ball milling circuit is considered for mineral processing of Cu and Mo flotation. A center line dam is adopted for the tailing dam construction for tailing disposal [3] [4].

2. Geotechnical, Geology and Hydrology Conditions

2.1. Geological Characteristics of the Ore Body

Mineralization in the multi-phase porphyry body has formed a cylindrical ore body consisting of disseminated mineral veins [5] [6] [7] [8]. The mineralized zone in a dome shape is over 2300 m long, 600 - 800 m wide, and 1000 m high. The predominant elements are copper, together with gold, silver, molybdenum, sulfur and other minerals. The main ore body at the center of the mineralized zone formed in the potassic and the silicified-sericitolite zone in the center of the porphyry rock body. This formation generally influences the local rock mass, tectonic fracture and wall-rock alteration. The main ore-bearing rock is beschtauite, together with quartz diorite porphyrite and granodiorite porphyry. The physical and geotechnical properties of the main rocks are shown in **Table 1**.

2.2. Regional Geological Structure

Studies show that the intense geological-tectonic activity in the mining area resulted in fractures and well developed folds [9] [10]. The tectonic is generally anticlinorium of Hongshan consisting of many linear NNW folds and synthetic

Table 1. Mean geotechnical properties of rocks.

Ore	Density (t/m^3)	Elastic modulus (GPa)	Poisson ratio	Strength (MPa)		Cohesion (MPa)	Longitudinal wave velocity (m/s)	Internal friction angle
				Compressive	Tensile			
Beschtauite	2.70	54.58	0.27	127.96	7.07	22.06	5551	47.31˚
Diorite porphyrite	2.76	58.68	0.25	185.67	12.29	22.70	5541	41.18˚
Marble	2.66	47.17	0.26	126.38	8.65	27.17	5375	44.51˚
Hornstone	2.77	57.31	0.17	192.51	14.72	32.49	5397	40.03˚

faults. NNW direction Geza fracture is the main fracture with long-term and inherited movement and it is considered as a rock and ore-transferring structure. The Geza fracture within the area is 57 km long, dipping to the east at about 41˚. The fracture is a periodically active reverse fault. The secondary NW fracture and EW fault are also well-developed, which are principal thrust wrench faults. The rock mass, especially the mineralized zone, contains abundant fractures in all directions with predominantly steep dip angles (67˚ - 85˚). Typical fracture is less than 2 mm in width and 0.1 - 2.0 m in length. They are mainly concentrated in the center part of the mineralized zone containing the porphyry mass with approximately 10/m fracture density [11] [12].

2.2.1. Regional Stratum

The outcrop of the stratum is mainly Triassic [13] [14] [15]. In chronological order, they are the Niru formation, Qugasi formation, Tumugou formation and Lamaya formation. Within the mining area, the Quaternary crops are out in local areas. Niru formation is present in the southeastern Rerong-Dijiton area. Qugasi formation and underlying Niru formation are separated by a fault. Tumugou formation consists of volcaniclastic rocks, which are partially contacted with the underlying Qugasi formation. Lamaya formation is in full contact with the Tumugou formation, consisting of two lithologic segments.

2.2.2. Hydrogeology

The average annual precipitation in the area is 619.9 mm, in which the rainy season accounts for 87.1%. The precipitation increases with the altitude, with an increase rate of 20 - 40 mm/100m in altitude. In the mining area, the largest gully has a flow rate of 180L/s in the rainy season and a smaller gully on the west side has a flow rate of 50 L/s. The lowest base level of erosion is nearby Pulang Valley, which altitude is 3250 m RL.

The main underground water is atmospheric precipitation combined with surface stream water, water in rock fractures and the glacial sediment pore aquifer. The groundwater reported during the mine development is mainly associated with water in faults and fractured rock. After the third gully is cut off during the beginning of the block caving, both the upstream rainfall and surface water will enter the cave, resulting in a sharp increase in underground water flow. The catchment area is estimated at 2.8 square kilometers. The estimated surface water inflow to the cave is 9000 m^3/d in the rainy season and 2000 m^3/d in the dry season. The maximum water inflow at a heavy rain event could reach 81,000 m^3/d. With the groundwater progressively being dried out, the total water inflow in tunnels will gradually decrease. To date, the average water inflow to the underground tunnels is between 505 and 3325 m^3/d.

2.3. Cavability and Fragmentation Assessment

The rock cavability of the initial mining area can be classified into four categories based on the studies, with a majority of rock (e.g., main ore body) considered suitable for the block-caving method. The rock cavability of the hanging wall is the worst unsuitable and the footwall between the hanging wall and the ore body. The large zone in the center of the main ore body at 3770 m RL (where Cu grade >0.3%) at the footwall is rated as just stable rock. The same zone at 3600 m RL is rated as less stable rock, which will likely have negative impacts on the block caving method, thus requiring special attention during mine design and ore drawing management [16].

In the initial mining block above 3170 m RL, the estimated in-situ P_{60} (60% passing this size) block size is 1.65 m, while the estimated P40 is 1.26 m. The estimated P60 in-situ block size for individual smaller mineralized zone defined by each exploration gridline ranges from 1.22 m to 2.23 m [17] [18] [19]. The hanging wall zone is estimated to have coarser fragmentation, while the footwall zone will have finer fragmentation. Categorized by lithology, the fragmentation of quartz diorite porphyrite will be the poorest, followed by beschtauite, granodiorite porphyry and hornstone zone. The block shape is predominated by slender and slender-flat. Categorized by cavability, the ore-bearing rock block size may increase gradually with a reduced ore grade. In different zones, no obvious difference in block shape has been observed [20].

3. Mining Method and Technique

3.1. Mining Studies

Technical and economic comparison of open-pit mining, underground mining and a combination of open-pit and underground mining methods was evaluated for the mine operation. Based on low capital expenditure, a short payback period, fast production ramp-up, and high recovery of the resources, the initial proposed plan was the combination of open-pit and underground mining methods. However, due to the stringent environmental requirements, open-pit mining was abandoned. The underground block-caving mining method was selected. This method has minimized the impacts on the environments as the waste dump (approximately 7.2 hm^2) was no longer required [21] [22].

3.2. The Block Caving Mining Method

The large, vertical ore body with good continuity will facilitate progressive caving, but the relatively low ore grade is less suitable for selective mining. No spontaneous combustion potential exists for the ore with relatively low clay content. Surface subsidence is allowed. The factors in all supported the block caving method as the preferred mining technique for this mine operation.

Based on the geometry and geotechnical properties, a single panel continuous caving scheme was determined as the mining method for the first-stage production above 3720 m RL. The maximal caving height is 370 m and an average of 200 m for the initial caving block. Four levels (**Figure 1**) of development were determined for the first-stage production, *i.e.*, a rail haulage at 3660 m RL level, a return-air at 3700 m RL level, a production at 3720 m RL level, and an undercut

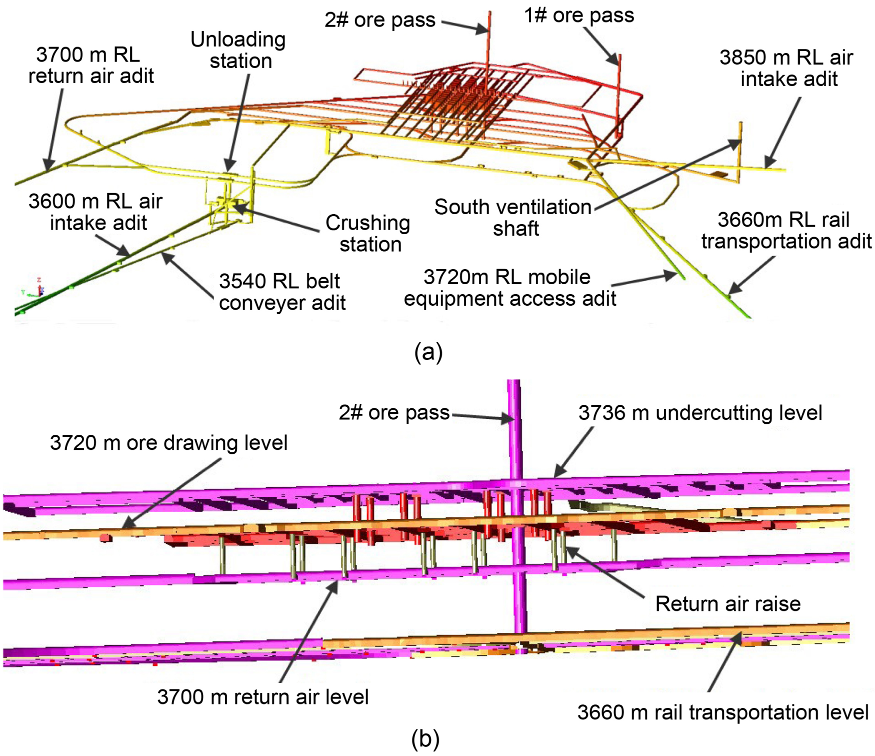

Figure 1. (a) General view and (b) local view of the development system.

at 3736 m RL level. The final development system is shown in **Figure 1**.

Ore cross-cuts are perpendicular to the ore body at a 30 m-interval. Ore draw points are laid out in a herringbone layout with an interval of 14 m. Both the hanging wall and the footwall drives are designed for load-haul-dumps (LHDs) to access the draw points. Ore passes #1 to #3 are placed within each ore cross-cut, depending on the width of the ore body at the crosscut location. A return raising air between the 3720 production and the 3700 ventilation level is installed for each ore pass. Undercut drifts are parallel to the ore crosscuts on the production level, with offset distances of 13 and 17 m (**Figure 2**). The undercutting height is placed at 15 m, with a long-hole drill and blast plan. Draw bells in the ore body employed to strike direction. When undercutting advances towards the east and west perimeters of the ore body, approximate 1400 m development is designed on the 3736 undercut level to facilitate the caving process.

The initial undercutting location is at the center of the ore body between No. 1 - 4 exploration grid lines with a relatively high ore grade. To control the advancing length of the undercutting line and reduce the damages caused by stress concentration, a diamond-shaped undercut pattern is adopted in the center of the panel. The undercutting will then separate in all four directions. Undercut drilling and blasting take place above a partially developed production or extraction level. Draw bells are blasted after stress is released post undercutting, usually following the 45˚-line rule. Draw bell drift is scheduled at least 20 m behind the undercutting advancing line, and production is at least 40 - 50 m behind the

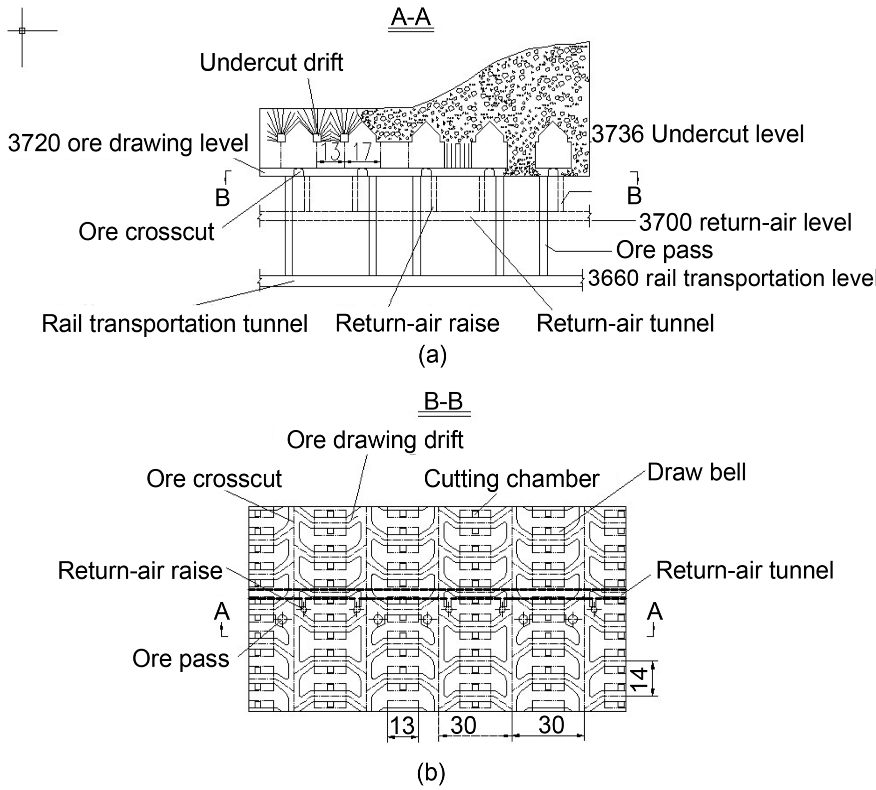

Figure 2. (a) Section view and (b) plan view of the production level at the Pulang copper mine.

undercutting advancing line. Ore drawing equipment is mainly electric 14 t-LHD with an average hauling distance of 150 m. Axera 7-190SUB hang-up machines will deal with potential hang-ups at draw points. There is a 1.2 m × 1.2 m grizzly for each ore pass in the production area, and oversized ores will be crushed with a mobile hydraulic hammer. The planned drawing rate is ≤0.2 m/d to ensure that the drawing rate is invariably lower than the caving rate. Evenly ore caving will be required and the contact surface between ore and waste rock will be minimized and uniform. The mining method is shown in **Figure 2**.

3.2.1. Haulage System

The haulage system is shown in **Figure 3**. Based on the terrain features and technical conditions, an adit development and conveyor transport method is adopted for the initial production above 3720 m RL. Located in the southwest of the mining area, the 3720 m level adit is accessible to personnel, material and mobile equipment. Sixteen LH514E electric LHDs and two LH514 diesel LHDs are designed for ore mucking. Ore is transferred down to the 3660 m RL rail transportation level via vertical ore passes. The rail transportation tunnel is in the southwest of the mining area, which is also used for transporting personnel, material, mobile equipment and rail equipment. At the bottom of each ore pass, a vibration ore drawing machine is installed to load the ore into mine cars. Driverless rail transport is planned via a closed-circuit rail line underground. On the 3660

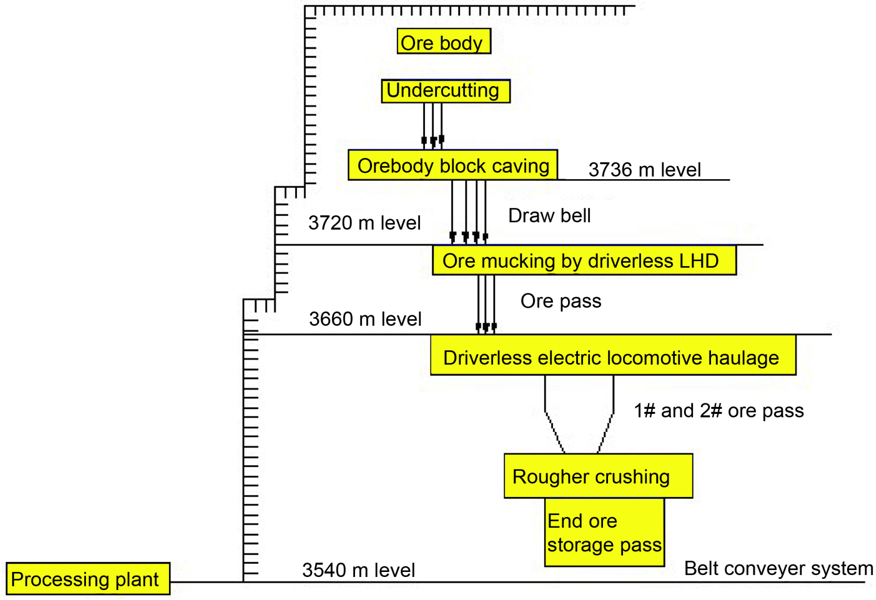

Figure 3. The schematic drawing of the development and haulage system.

level, two 40 t electric locomotives will haul up to ten 20 m^3 dumping mine trucks, with up to six haulage trains running simultaneously. The ore is transferred down to a crushing station at 3605 m RL. An air intake adit at 3600 m RL is connected to the crushing station, which is also used for fresh air intake and maintenance access for crushing equipment. The crushed ore is transferred down to the 3540 m RL crushed ore conveyer via an ore pass and it is then transported to the processing plant. The conveyor has two different slopes, 0.4% and 0.7%. The horizontal length, volume and operating speed of the belt conveyer are 3064 m, 3800 t/h and 4.0 m/s, respectively.

3.2.2. Underground Ventilation

The mine ventilation system is illustrated in Figure 4. Fresh air intakes of mine are through adits at 3600 m RL, 3660 m RL, 3720 m RL (mobile equipment access adit) and 3850 m RL levels. Auxiliary fans are placed to distribute the fresh air to development and production sites if required. Return airways are at 3700 m RL adit and a south ventilation shaft.

4. Cave to Mill

An integrated mine and mill approach would be necessary to coordinate mine schedules and beneficiation processes so that a satisfactory level of throughput and recovery can be achieved. A systems engineering approach for cave mine operations, termed cave to mill, has been developed to give existing and future block cave operations an opportunity to improve productivity. Both mine and mill models are set up at the beginning and continuously refined as the Pulang project progresses. The major objective of adjusting design and operational parameters within cave-to-mill is to maximize NPV. A central component is the ore block model, which is continuously refined during the Pulang project development

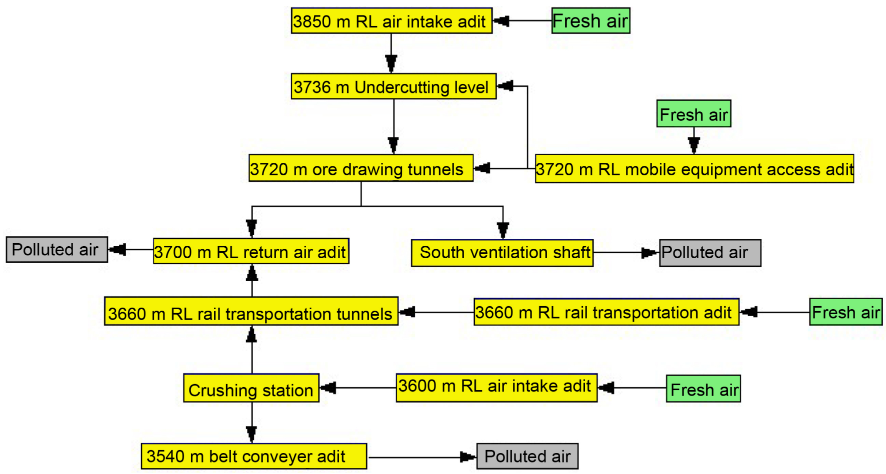

Figure 4. Schematic drawing of the ventilation system.

and operation through input of geotechnical, geological, and metallurgical information. At the exploration stage, initial access to an ore body is generally provided through exploratory drilling, allowing block models and design parameters to be established through the analysis of core samples. As the project progress toward development, excavations and boreholes provide access to additional sample and data, which can be used to repopulate block models. Following plant commissioning, logs of mine and mill performance, such as fragment size measurements and specific energy consumption of mill processes, can serve to calibrate predictive models and refine block models.

4.1. Production Schedules

The production schedule refers to the sequence of drawing ore from draw points. It provides the possibility to control properties of the plant feed that affect mill performance when considered as a means to blend ore types in a fashion that increases mill productivity. By applying 3D imaging-based technology, cave fragmentation can be auto-measured online. These fragmentation data provide the opportunity to improve predictions of draw point availability and the resolution of mixing algorithms, better define the profile of particle flow and evaluate the variation in comminution requirements with respect to crushing and grinding equipment in the mill. Work on cave-to-mill development includes the integration of fragmentation and metallurgical parameters, such as grade, metallurgical recovery and comminution-specific energy, for consideration in the footprint specification and production scheduling solutions. In this way, the opportunity to blend ores based on their associated mill performance is incorporated into the production schedule.

4.2. Metallurgical Characterization

During the process design stage, characterization of the metallurgical properties of an ore is carried out to determine the economic implication of choosing certain comminution and beneficiation processes. The comminution circuit for the Pulang copper mine is shown in **Figure 5**. For cave-to-mill, High-Pressure Grinding Roll (HPGR) based circuit can benefit an operation since the throughput potential for HPGRs is less sensitive to variations in ore hardness than SAG mills, and therefore, priority can be given to other metallurgical opportunities such as metal recovery.

A geometallurgical approach is incorporated into cave-to-mill: ores that show similar responses to a nominated metallurgical testing regimen are grouped into ore domains. A challenge associated with handling geometallurgical data is the fact that not all geometallurgical characteristics are additive. For instance, Bond ball mill work indices are not additive and need to be converted into alternative units through simulation, in order to populate the block model. Alternatively, blend-response models have been identified as a solution to modeling mill performance for a variety of ore types.

In order to capture the degree of ore heterogeneity in terms of mill performance, small volume tests are carried out with respect to the process circuits being considered for implementation. Laboratory scale tests for newer comminution technologies, such as HPGRs and vertical stirred mills, are yet to be accepted by the industry. A particularly relevant development in this area includes piston press testing procedures that have been developed for estimating HPGR performance including specific energy requirements.

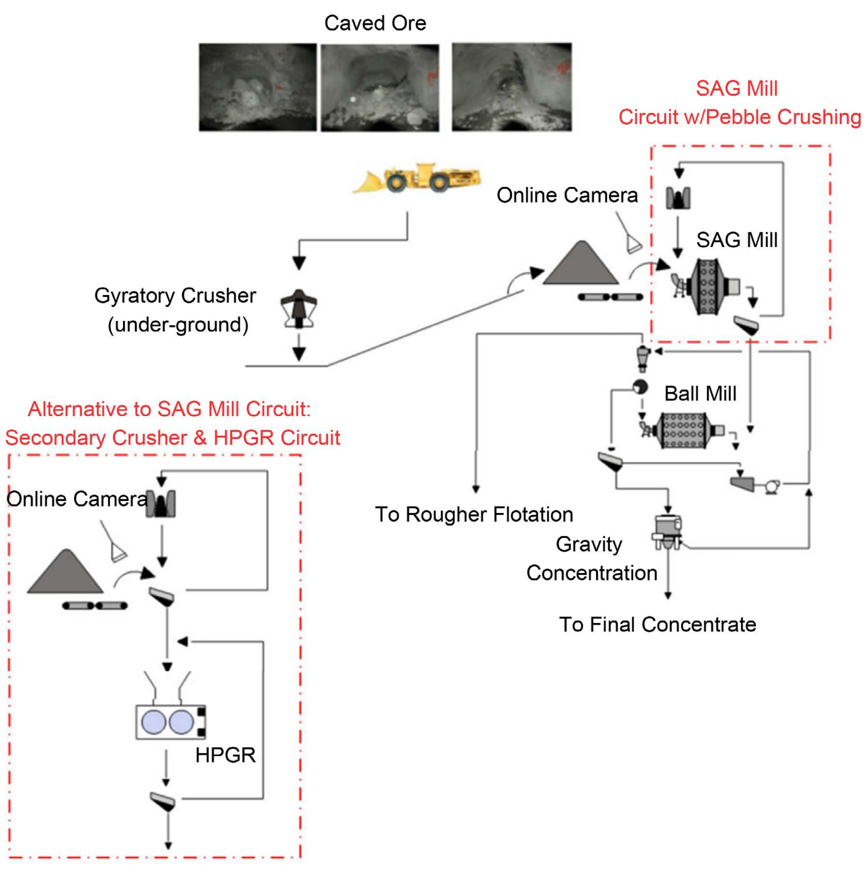

Figure 5. Pulang comminution circuit flowsheets.

4.3. Lithology Sensors

Owing to their nature and design, cave mines lend themselves to automation such as the incorporation of sensor systems to support planning and operational decisions. These systems can be used to develop operational strategies that focus on cave-to-mill objectives such as maximizing the NPV. There is a degree of heterogeneity in all ore deposits related to variations in fragmentation as well as variations in grades. The amount of dilution would vary depending on a number of geological factors such as lithological rock types as well as design criteria such as cutoff grade. Where heterogeneity exists, there is an opportunity to use sensors to discriminate between ore and waste.

Currently, work is underway to commercialize technologies by incorporating sensors (e.g. electromagnetic, X-ray fluorescence and spectrographic sensors) into material handling systems such as in shovels and on conveyors. For Pulang mine, there are additional opportunities to place sensors in draw points, feeders and storage/surge bins. Sensor systems with data telemetry provide real-time information that can be applied to improve the operation of the downstream plant. A change in lithology could trigger adjustments to grinding circuit operation and reagent addition for flotation. Rather than reacting to more changes, the information can be applied in a proactive manner. Sensor-based systems represent an emerging technology that can have a large impact on the Pulang copper mine which will be operated in the future, supporting operations that are more responsive to ore heterogeneity and therefore more dynamic.

5. The Challenges

5.1. Altitude Considerations

Early in the Pulang project conducted extensive research into the effects of working at high altitudes and the results of these studies are reflected in the design of the facilities and the method of working. By far the most serious consideration regarding altitude is the effect on people and particularly the issue of altitude sickness.

Although more serious forms of altitude sickness can occur Acute Mountain Sickness (AMS), this may occur at elevations as low as 2450 meters and most people are affected above 3000 meters. It is usually felt within a few hours of arrival and symptoms include fatigue, headache, nausea, loss of appetite and difficulty in sleeping. Normally it requires no treatment other than typical headache relief medication and symptoms normally disappear within 2 - 3 days. Although the effects may be mitigated by frequent visits to altitude they are generally experienced on every visit.

The research studies indicated that the effects of AMS could be mitigated by locating an accommodation camp at Hutiaoxia, some 25 km from the mine site and at an elevation of 2800 meters, so that only working hours are spent at higher altitudes. It was also decided to place in the same location the offices of the mine management staff and all personnel not required to be physically present at the mine itself.

Design and equipment selection also necessitated altitude considerations. The lower air density significantly reduces the cooling efficiency of fans on electric motors; for example, design specifications had to take this into account. Other equipment such as compressors had to be derated and the mine truck engine efficiencies were affected.

Ergonomic considerations were important in the design of the concentrator. The opening floor has a single platform level from the mills through the rougher flotation area and provides a walkway at the same level through to the second cleaners and regrind area. Elevators are provided in the mill building, the crushing plant, the mill offices, laboratories and the change house are all located within the same complex. The plant layout is relatively spacious which permits the use of mobile equipment for lifting and also cleanup.

5.2. Climatic and Seismic Conditions

Temperatures at the site are generally low. During the day temperatures average between −3˚C to 11˚C and at night they are generally below freezing, sometimes as low as −20˚C [23]. Design parameters, therefore, have to consider this, particularly with respect to protection against freezing. Examples are fire protection systems on external conveyors, where the fire water lines have to be dry-charge systems and the requirement for heat tracing and insulation of critical water and reagent delivery lines.

The heat balance over the mill building indicated that the energy produced from the various drives and from the milling process would be sufficient to maintain acceptable temperatures within the building during normal operations, even with one mill line down for maintenance. During commissioning however the mill building was still cold and therefore many of the internal lines, particularly gland seal water systems, had to be heat traced.

High-energy winds are also common and this had a significant effect on the design of the mill building and other structures. One of the first impressions of the Pulang mill is the large amount of structural steel in the building and this is largely because of the wind pressures (the ore stockpile building and the concentrator contain almost 10,000 tons of structural steel). The design wind speed is 140 km/h with a wind pressure of 90 kg/m^2.

This wind also caused some problems with the mooring of the tailings water reclaim barge. The water lines from the barge to the shore are supported by pontoons which were designed to be flexible in the vertical direction only. Movement of the barge due to wind caused damage to the pontoon linkages; thereby the moorings required a redesign.

Shangri-La County is part of a very active seismic zone. Seismic events occur frequently – for example, during a 4-week period between October and November 2012, ten tremors of magnitude 4.7 Richer or greater were recorded in the northern of the county. The seismic risk for Pulang, defined as the probability of

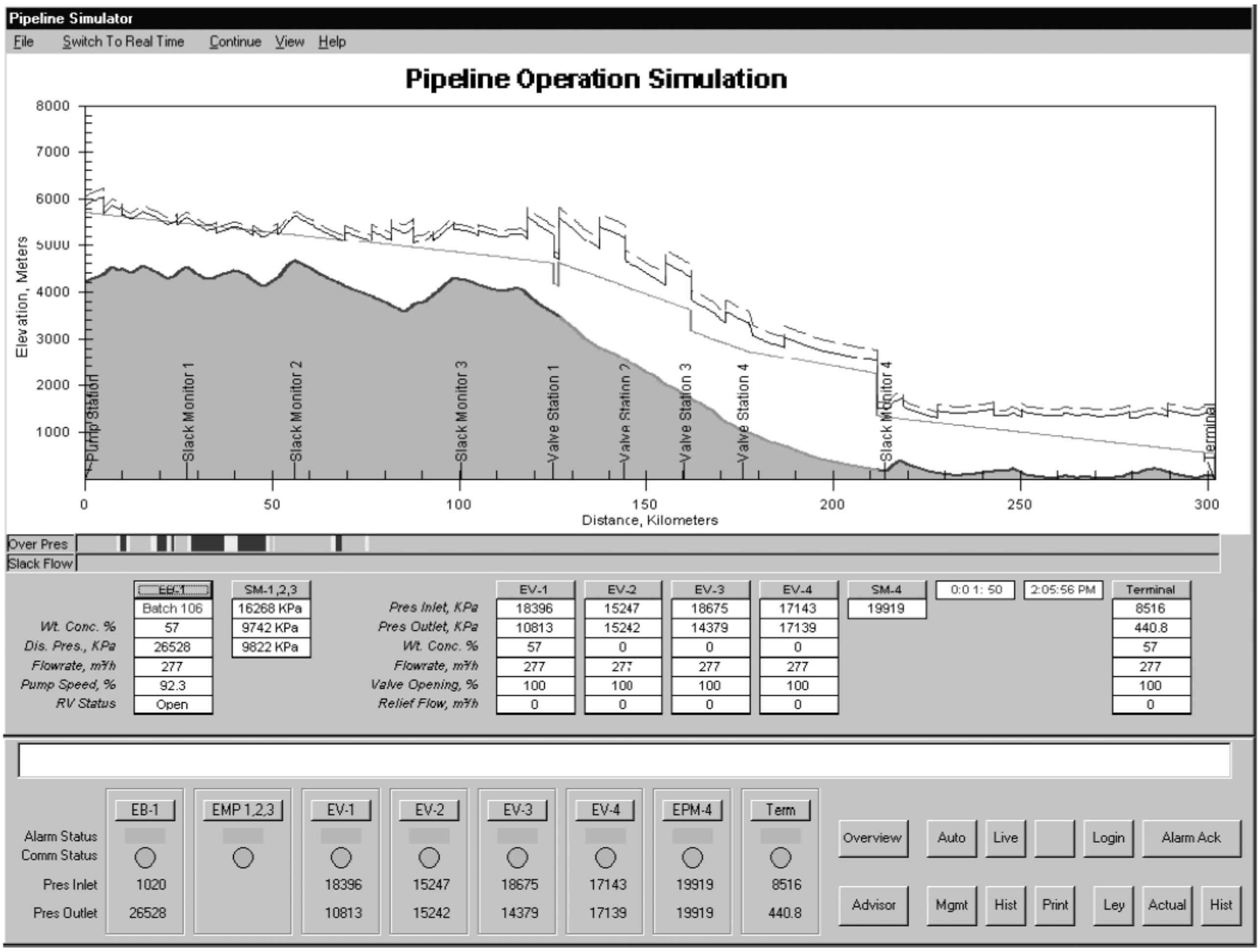

Figure 6. Pipeline simulation screenshot.

occurrence of an earthquake of magnitude 7.5 Richer with an acceleration greater than or equal to 0.1 g during one year, is assumed at 20% with a return period of 30 years. Pulang site is classified as UBC Zone 4 and this also contributes to the heavy structural design of the buildings.

5.3. Long Distance Slurry Pipelines in Mountainous Regions

Tailings Transportation is designed by a pipeline hydrotransport system. The pipeline is located in mountainous terrain (Yulangpei district) and the entire length is 30 km which connects the processing plant and the tailing dam. This caused technical issues that need to be overcome in the design and operation of mountain pipelines that do not affect pipelines on more level terrain. One of the key factors in designing a pipeline running through mountainous terrain is to determine the maximum allowable slope. This slope would depend on the slurry properties and to some extent the pipe wall material. Selecting a route that would minimize the pumping required, and establishing a trade-off study between the cost (and added hydraulic complexity) of a valve station and the cost of additional steel, can also result in a far superior system.

Due to the complexity, the correct actions to take when controlling a slurry pipeline are sometimes counter-intuitive, so there may be a rather long operator-training curve. The closing of the valves at the various points of the pipeline, the timing of the valve stroke, the shutdown of the mainline pulps, etc. all need to be carefully timed in order to prevent over-pressure or activation of pressure release devices. As a result, people operating pipelines were trained using simulators. Simulation models allow an operator-trainee to perform every pipeline function in the model and see the steady state and the transient results. **Figure 6** shows a typical screen shot from a pipeline simulator which was used in Pulang.

5.4. Environmental Impacts

The mine construction and mining is a key factor in the development of Shangri-La County. The problem is how to best integrate mine economics with broader "nation building" needs. Of course, "development" is not always desirable. Clear-cutting of first growth forests, slash and burn agriculture are often considered problematic. Even "desirable" may be problematic if it impacts the lives of indigenous people. In fact, in the Shangri-La County, a major driver towards Pulang mine construction is to limit general access to ecologically and/or anthropologically sensitive areas.

6. Summary

Although the block-caving method has been widely used in some other countries with large mining sectors, this method is still rarely applied in China. To date, only Tongkuangyu Copper Mine at the Zhong-tiao Mountain has partially been successfully used in China. This paper describes the development and the experiences of the block-caving mining method applied in China's biggest underground nonferrous mine Pulang copper mine. Furthermore, linkages between the key cave and mill parameters have been established to hold significant value within the cave-to-mill approach. A few major challenges such as high attitude are recognized and carefully considered during the detailed design and construction stages.

This study will give some guidelines for some mining sectors having similar technical conditions. Further research and investigation into the block-caving method will be carried out during the ongoing mine construction and production phases to ensure the mine production and safety.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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