Mining Open Pit through the Sishen Cave

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Abstract

The Sishen cave was first discovered in 1978 when a drilling sub-contractor drilled into the cavity at a depth of 120m. Over the following years the shape and extent of the cave was determined by exploration drilling, gravity surveys and information gleaned from video recordings. The most feasible mining method was deemed to be backfilling of the cavity and to exploit the ore with conventional truck and shovel operations. In devising a mining method, the risk of a large scale catastrophic roof collapse was identified as the main driver. In order to address the risk a three prong strategy was adopted which included the determination of the minimum roof thickness, a backfill strategy and a double bench blasting practice.

In order to safely mine the cave, the slope stability radar was used to monitor the working surface in real time for subsidence. The method successfully detected numerous subsidence events which were managed without incident. Laser cavity monitoring was used to determine the remaining void extents after backfill and to monitor the roof thickness for fall out.

Four subsidence events occurred from 1998 to 2010 all of which were monitored and managed. The cave was successfully mined out in 2010 without any lost time injuries or damage incidents as testament to the design of the solution, the management of the risk and the commitment and collaboration of geotechnical engineering and production personnel (drill, blast, load and haul).

1 Introduction

Sishen Iron Ore Mine is located in the Northern Cape Province of South Africa, about 230 km north-east of the town of Upington and 280 km north-west of Kimberley (Figure 1).

Figure 1. Location of Anglo Kumba Iron Ore operations.
The mine was has been operational since 1953 and has 21 years life of mine remaining. Sishen mine produced 42Mt of high grade hematite in 2010, 36Mt of which was exported via the Sishen-Saldanha rail line to the international market. The balance of production is sold to the local steel industry.

The Sishen cave was first discovered in 1978 when a drilling sub-contractor drilled into the cavity at a depth of 120m. The cave, located in the south mine area was developed by groundwater leaching into the lower lying dolomite formations, presumably along weak fractured zones. The cavity migrated upwards by collapse of the overlying lithologies until it reached the iron formation, ranging in thickness from 45m to 130m (Figure 2). This competent layer prevented further formation of the cavity, resulting in a stable roof (Van Der Berg, 1988). In the early years the shape and extent of the cave was determined by exploration drilling, gravity surveys and information gleamed from video recordings.

The roof of the cave comprises 6.8Mt of high grade hematite at an average stripping ratio of 0.413. In addition 18Mt of iron ore in close proximity to the structure could be sterilised should a method not be devised which could safely excavate the cave.

2 Mining methodology and practice

The decision to mine the roof of the cave was made in 1989. In 1993 an 80m deep shaft was sunk through the roof into the southern portion, thereby gaining access. As the cave was 90% full of water the South African Speleological society performed a sonar survey to determine the exact extents of the cavity. A 3 dimensional model was constructed which provided the first accurate dimensions of the cavity (dipping at approximately 37 degrees, 260m along dip and 70m along strike with a total volume of 261,391m³) (Figure 3).

![Diagram of the cave formation](image)

Figure 2. The cave was formed through upward migration of a solution cavity in the dolomite until it reached the iron formation.
2.1 Mining method

The most feasible mining method was deemed to be backfilling of the cavity and to exploit the ore with conventional truck and shovel operations. In devising a mining method, the risk of a large scale catastrophic roof collapse was identified as the main driver. As such a three prong strategy was adopted in order to reduce the probability of such an event:

- Minimum roof thickness – In order to determine equipment selection for mining in the vicinity of the cave, an investigation was done to establish a minimum thickness of roof (Carvill, 1994). The Voussoir arch theory was applied to the problem as the theory considers the plate that can be left over an opening without buckling, shearing or compressive failure of the plate margins. It also assumes that the rock mass has ubiquitous vertical / sub-vertical joints which is analogous to the situation at Sishen. Two and three dimensional stress analysis techniques were employed to assess the effect of a superimposed point load of 328 tons, i.e. a fully laden truck as this would be the heaviest piece of equipment operating on the cave.

The minimum beam thickness was determined to be 5m with a factor of safety of 1.3 for the given conditions and point load. When considering the minimum working thickness of the beam the following additional uncertainties which at the time could not be accounted for in the design were taken into considerations:

- Geological variation and unknown structures
- Reduction in rock mass strength as a result of blasting damage
- The effect of having a second free face and the potential for loss of material from the hanging wall of the cave.

Considering the bench height at Sishen is 12.5m a 25m minimum (double bench) roof thickness was selected.
• Backfill – the cave would be backfilled via a series of shafts constructed throughout the life of the project with competent quartzite. The purpose of the quartzite fill is 3 fold, firstly it reduces the amount of ore lost as a result of collapse of the roof into the cavity, secondly, it provides a layer visually different form the ore, therefore reducing contamination during mining, and thirdly to reduce the consequences of a roof collapse by reducing the fall distance of the roof and therefore the impact on surface where mining machinery will be present (Mc Gavigan, Lamprecht, 2005).

• Double bench drilling and blasting – depending on the position of the blast blocks relative to the cavity and the recommended 15m safe roof thickness, a combination of single bench (12.5m) and double bench (25m) would be mined. The blasting of the 25m benches would result in the collapse of the block into the cavity thereby filling any remaining voids between the quartzite fill (Mc Gavigan, 2006).

Based on the chosen mining method, several strategies were devised to ensure that the method could be safely and successfully implemented, these include:

• Shaft design and construction
• Equipment selection
• Mining sequence
• Surface stability monitoring
• Monitoring of minimum roof thickness

2.2 Shaft design and construction

Shafts were constructed using the drop raise method. A 20 inch (508mm) cut hole was drilled into the cave with additional 165mm holes as indicated in Figure 4. Gas bags were used to seal the holes and the shafts was blasted in 5-6 meter lifts. The depths of the shafts varied from 80m to 39m.

Figure 4. Shaft blast design.
2.3 Equipment selection

Based on the risk of catastrophic roof collapse, the assumptions and uncertainty in the design and geology, the following equipment selection criterion was set:

- Maximum Mass – 328t
- Loading equipment must be mobile in order to react and evacuate quickly in the event of an incident i.e. no track mounted loading equipment was used.

Based on the above the following equipment was selected:

- Trucks – Komatsu 730E, Unit Rigs or smaller
- Shovel – Front End Wheel Loaders (CAT 994 or Komatsu WA 1200).
- Drills – 60t, 310mm production drills (Bucyrus Erie 49 R or P&H 120)

2.4 Mining and backfill sequence

Four shafts were planned for the life of the project. The sequencing of the shafts would proceed from South (shallow) to North (deep) and would be followed by backfilling (Figs. 5, 6, 7 and 8).

All shafts were backfilled by short dumping and dozing (Figure 6). On completion of backfilling, the position of the shafts were demarcated and barricaded at all times (Figure 7) due to the risk of sudden collapse of the shaft material as a result of hang-up within the shaft. One such incident was experienced during the project.

Figure 5. Shaft and backfill sequencing.
The mining cycle (drilling, blasting, loading and hauling) would occur in the same direction as the development of the shafts to ensure that mining on areas less than the minimum roof thickness always proceeded from stable ground - either intact rock or backfill, towards the void. Any potential large scale instability would therefore occur ahead (north) of the mining unit. Loading on was only permitted during daylight hours. Figure 9 shows the mining cycle. Detailed loading plans were provided to production personnel which specified the loading equipment, loading direction, position of shafts and any other hazards identified by the geotechnical department (Figure 10).
Figure 9. Mining sequence.
2.5 Stability monitoring

Three monitoring techniques were applied in order to detect any potential roof subsidence during mining activities.

2.5.1 GPS and optical prism monitoring

A stability monitoring network comprising GPS beacons and prism stations were constructed on the roof for the cave before mining commenced. All of the stations were manually recorded on a daily basis. No significant subsidence trends were detected. The use of discrete point monitoring proved to be inaccurate and problematic as the cave was an active production area and the survey stations hindered the movement of mining equipment and were often damaged.

2.5.2 Slope Stability Radar (SSR) monitoring

Sishen mine uses radar technology as part of the slope risk management methodology and was utilized to monitor for potential subsidence associated with the mining of the cave.

The first drill block where the roof of the cave was close to the specified 15m minimum, was scheduled to be mined in November 2004. No visual signs of instability were noted. The SSR was setup (Figure 11) to monitor the surface of the block to be drilled towards the middle of October 2004.

The SSR measures the deformation in the direction of the radar beam, rather than in the true direction of movement. The true directional deformation (Figure 10) can be calculated if the direction of the displacement relative to the radar beam is known.

The SSR scanned an area of approximately 120m x 300m in 6 minute scan intervals. The results of the scans showed that a single area of definite subsidence was developing around the second southern most shaft, initially no visual signs of subsidence were apparent. Linear deformations of 11mm/day were detected which equate to actual deformations of 38.7mm/day (Figure 12).
The results of the scan showed that the initial movement detected by the SSR was slowing. This was interpreted as the roof of the cave subsiding and coming to rest on the underlying back fill. The result of the data was discussed with the relevant production employees and they were confident to commence operations in the area (Mc Gavigan, 2006).
The accurate deformation data and delineation of the subsidence area provided by the SSR enabled detailed drilling plans to be provided to the relevant employees. The main aim of the plans was to ensure that the production dills were positioned on stable ground and that employees were aware to the subsidence area and associated risks (Mc Gavigan, 2006).

An area of concern and limitation the SSR in this application is that the coverage is dependent on line of sight and a blind spot exists where mining equipment obscures the radar beam. In order to manage the risk of subsidence behind equipment, drilling was only permitted during daylight shifts, the work area was evacuated at night and the radar scanned to determine subsidence trends in the areas obscured during daylight drilling. Furthermore the drill rig sampler was used as a spotter around the drill and trained to identify signs of instability (Mc Gavigan, 2006).

While scanning in a non production situation, the radar data can be accessed remotely and it is not necessary for geotechnical input. In a production situation, however, it is necessary for the geotechnical department to man the SSR; the function of this is four fold (Mc Gavigan, 2006):

i. Unique scan areas were set up for each hole.
ii. No prior data was available on subsidence or failure trends; it was therefore not possible to determine alarm thresholds. Real time decisions were made based on the data as it was collected at the SSR.
iii. Warnings and evacuation orders could be given directly to the equipment operators and it was not necessary to rely on the dispatch operator to give these instructions.
iv. Inspections by the geotechnical engineer could be carried out immediately after the subsidence was detected by the SSR.

One evacuation has occurred during the mining of the cave as result of sudden subsidence detected by the SSR. During the drilling of a blast hole, actual deformation of 18.6mm/hour were detected around the drill rig. The operator and assistant were immediately evacuated and the area inspected by the geotechnical personnel supervising the radar, and drilling process. It was clear after inspection that the deformation detected by the SSR was caused by further subsidence, evidence of which could be seen in widening tension cracks (Mc Gavigan, 2006). 

The radar data was inspected for an additional 20 minutes and it was observed that the velocity of deformation was slowing (Figure 13).

Based on his data and the general tendency that the roof was coming to rest on the underlying back fill material, the area was declared safe to continue and the hole was completed. Quartzite drill chips were expelled from the hole at a depth of 22m proving that the roof was supported by the underlying backfill and confirming the theory that the slowing deformation as a result of the support offered by the backfill (Mc Gavigan, 2006).

2.6 Monitoring of minimum roof thickness

After the construction of the third shaft, uncertainty existed as to the remaining extent of the cavity as significant production had occurred above the cave and the probability existed that a portion of the roof may have collapsed. Re-surveying the cave would ensure that the remaining shaft and benches were designed correctly and that 20m minimum roof thickness were maintained.

A cavity monitoring system, the Cavity Autoscanning Laser System (C-ALS) was lowered through four 165mm drill holes drilled into the cave. The data was processed, edited and a composite model of the remaining void was created for design purposes.

The scan showed the remaining void was only 12 meters high at maximum (Fig. 14). Very little to no roof collapse had occurred and the original void model and design was acceptable. This information was then utilized to confirm that the fourth shaft was positioned correctly to backfill the remaining void and that the remaining double benches were designed correctly to ensure the roof of the cave would adhere to the minimum roof thickness (Bester 2007).
3 Subsidence statistics

A total of 4 subsidence events occurred from 1998 to 2010 when the cave was actively mined (Table 1). All of the events were managed and resulted in no injuries, equipment damage or delay in production.
Table 1. Subsidence statistics 1998 to 2010.

<table>
<thead>
<tr>
<th>Date</th>
<th>Description</th>
<th>Rate</th>
<th>Measured by</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004-10-15</td>
<td>Subsidence and surface cracking</td>
<td>34mm/day</td>
<td>Radar</td>
<td>Subsidence around southern most shaft, non production setting</td>
</tr>
<tr>
<td>2004-11-23</td>
<td>Subsidence and surface cracking</td>
<td>18.6mm/h</td>
<td>Radar</td>
<td>Rapid subsidence during drilling of production block, drill evacuates. Area monitored and deemed safe – movement decreased.</td>
</tr>
<tr>
<td>2005-02-24</td>
<td>Shaft subsidence</td>
<td>Instantaneous, no evidence of failure</td>
<td>Radar</td>
<td>Failure of backfilled shaft material, area barricaded no incident. Failure occurred between radar scans (12 minutes) no indication of failure or preceding scans.</td>
</tr>
<tr>
<td>2008-06-21</td>
<td>Surface cracking</td>
<td>-</td>
<td>Visual</td>
<td>Surface cracks developed close to shaft, non production setting.</td>
</tr>
</tbody>
</table>

4 Conclusions
The Sishen cave was successfully mined from 1998 to 2010 without any lost time injuries or damage incidents.

In devising a mining method, the risk of large scale catastrophic roof collapse was identified as the main driver and a three prong strategy was adopted in order to reduce the probability of such an event, i.e. minimum roof thickness, backfilling with quartzite and double bench drilling and blasting.

The Slope Stability Radar was used to detect subsidence and has proved invaluable in the mining of the roof of the Sishen cave. The advantage of the system over conventional monitoring solutions was that the exact boundaries of the deformation can be determined in near real time, even with no visual indications of subsidence. This enabled compilation of proactive drilling and loading plans to ensure the safety of employees (Mc Gavigan, 2006).

All data collected from the radar and laser cavity scanning have proved the design, mining method and backfill performance. Effective monitoring tools, disciplined evacuation procedures and good communication led to informed employees that helped to dispel the fears associated with the mining of the roof of the cave.

Furthermore, the safe recovering of 6.86Mt of high grade ore attested to the design of the solution, the management of the risk and the commitment and collaboration of geotechnical engineering and production personnel (drill, blast, load and haul).

5 Acknowledgments
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6 References