Small Scale Open Pit Design with Limited Geotechnical Knowledge and Resources

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Abstract

The design of stable slopes for an open pit operation requires specialised knowledge of the geology and the material properties of the near surface weathered materials and underlying rock mass. In the current economic climate, gold mining companies are beginning to exploit small deposits and investigate the potential of deepening previously mined open pits. Due to the small size and short mine life of the pits, specialised geotechnical testing may not be included within the mining budgets. A project was conducted to investigate whether acceptable pit slope designs can be developed using the limited available information and readily available slope stability analysis software. The project studied three open pit operations in the Kalgoorlie area of Western Australia. One case study will be described in detail. The outcomes from the case studies are recommendations for designing similar open pits planned for the future.

1 Introduction

The Kalgoorlie Region has been mined extensively for over 100 years involving both underground and open pit operations. The majority of pits were mined in the 1980s and 1990s by a number of different companies and many of these are small, relatively shallow open pits. Ideally, open pits should be designed following comprehensive guidelines such as those published recently by Read and Stacey (2009). However, in many cases the regions gold is shallow, and contained in the completely weathered and transitional zones barely reaching fresh rock. The cost of specific geotechnical drill holes and conducting laboratory testing on the clay materials may not be economically viable. Some small companies may not have the available revenue to conduct specialised testing, buy expensive specialized computer software, or employ consulting geotechnical engineers.

Due to high turnover of geotechnical professionals and the loss of hard copy geotechnical design reports, it is now the task of the current geotechnical engineer to design stable slopes with what limited geotechnical knowledge and technical support is available. However, due to the number of historically mined open pits, it is proposed that to obtain acceptable design parameters, back analyses on the pits in close proximity to proposed new pits be undertaken.

2 Barrick Kanowna Operations

2.1 Location

The Barrick Kanowna Operations are in the Eastern Goldfields region of Western Australia approximately 600km east of the state capital of Perth (Figure 1). The Barrick Kanowna granted tenement holdings, covering just over 41,000 hectares, are concentrated in a 50km to 80km sector trending northward from the city of Kalgoorlie-Boulder and surround the well known mining camps of Kanowna and Kundana. At the time of the study, Barrick Kanowna Operations consisted of two underground gold mines (Kanowna Belle and Raleigh), one open pit (Moonbeam) and one mill complex (Kanowna Belle).
2.2 Geology

The Barrick Kanowna Operations are located within the Eastern Goldfields province of the Archean-aged Yilgarn Craton in Western Australia (Figure 2). The Yilgarn Craton is made up of north-north-westerly trending greenstone belts and granitic intrusions. Greenstone successions of the Southern part of the Eastern Goldfields are divided into elongate structural-stratigraphic terranes separated by regional NNW-trending faults. The Kalgoorlie Operations lie within the Norseman–Wiluna greenstone belt, an 800 kilometre long, 200 kilometre wide greenstone succession, that is characterized by a western portion consisting of a thick sequence of ‘rift-phase’ greenstones (abundant komatiites), and an eastern portion characterized by felsic volcanic centres.
The belt is divided into a number of separate terranes; Kalgoorlie-Boulder city falls within the Kalgoorlie Terrane (Swager, 1996). The regional stratigraphy of the Kalgoorlie Terrane consists of a lower basalt, komatiite upper basalt and overlying felsic volcanic and volcaniclastic rocks (Swager, 1996). Within this terrane there are several major domains (Figure 3) bounded by a number of faults and shear zones (Swager et al., 1990). Kundana, the domain for which the detailed case study will be presented, lies to the south-west, straddles the craton-scale Zuleika shear zone which separates the Ora Banda and Coolgardie Domains. The deposits are hosted in a very structurally complex sequence of sediments, volcaniclastic, mafic and ultramafic volcanic and intrusive rocks. The general sequence, from west to east, consists of Komatiite, felsic volcanics and sedimentary derived rocks, granophyric quartz dolerite, high magnesium basalt (Bent Tree Basalt), feldspar-phyric basalt (Victorious or Cat Rock Basalt), pyritic carbonaceous shale and intermediate volcanic and volcaniclastic rocks (Black Flag Beds) (Lea, 1998).

Figure 3. Geological Domains, Kalgoorlie Region (after Golenya, 2010).
2.3 Depths of weathering
It is difficult to generalise what the depth to complete oxidation is across the Kalgoorlie Terrane, depths of weathering vary considerably from zero on elevated basement geology where there is considerable out-crop, to over 100 metres in low-lying landscapes over old drainage systems.

2.4 Groundwater
The standing water table depths across the mining camps are quite similar at about 30m below the surface.

2.5 Climate
The Barrick Kanowna deposits are located in a semi-arid environment (Golenya, 2010): The average daily maximum temperature is 33.6°C in January and 16.5°C in July. Average minimum temperatures are 18°C in January and 5°C in July. Annual rainfall is 260 millimetres on an average of 65 days. Evaporation rates are high with an annual average evaporation of 2,664mm. The climate is such that operations, both underground and on surface, are continuous throughout the year.

3 Methodology
A number of case studies were used to evaluate the design process in terms of observed performance. Each case study used the following methodology:

- Develop a geological model.
- Define a geotechnical model.
- Conduct slope stability analyses.
- Specify slope design.
- Observe performance and assess design parameters.

This methodology will be demonstrated with a case study of a pit mined in the Kundana region.

4 Case study
The Moonbeam Pit in the Kundana region will be used for the detailed case study.

4.1 Geological model
The Kundana deposits are hosted by a structurally prepared sequence of sediments, volcaniclastics, mafic and ultramafic volcanic and intrusive rocks typical of the greenstone sequences in the Archean Yilgarn Block. The geology at Moonbeam is typical of the geology in the Kundana area. The bedrock lithologies are Archean mafic rocks. The lithologies are weathered to a depth of 30 to 50m to form a saprolite profile of clays, grading into moderately weathered and fresh rock as shown in Figure 4. The mineralisation is associated with a narrow sub vertical quartz vein dipping approximately 80 degrees. The geology at Moonbeam from regional information is shown in Figure 5 with the Bent Tree Basalt (MB), Victorious Basalt (MBP), Volcaniclastic sediments (SVG), Intermediate Volcanics - Andesite (IV) and dolerite (MG2, MD) lithologies. The sequence is covered in 5m of alluvial tertiary clays. The proposed Moonbeam pit shell is also shown with a small Christmas pit extension to the north.

4.2 Previous mining in the vicinity
Mining of Moonbeam pit commenced in February 2000 and was completed at the end of February 2001. The design and performance of this existing Moonbeam pit was reviewed to enable Geotechnical Assessment for Stage 2. The existing pit appeared to have been mined with 45 degree batters and 5m berms in completely
oxidized material (alluvium and saprolite), and 60 degree batters, 5 m berms in fresh rock. The overall slope angle was approximately 38 degrees, over the 53m pit depth (Feltus, 2009).

A review of the performance of the existing pit indicated the wall stability was acceptable for the design parameters used. The end of mine survey pit pickup shows poorly defined berms in the fresh rock suggesting berm crests were difficult to maintain once blasting was required. This was due to a combination of structures and poor blasting techniques.

During mining, a significant failure occurred in the northeast section of the pit from the surface through the saprolites to approximately 315mRL (approximately the base of oxide rock). This failure appears to have had the Lucifer Fault as its northern release surface (Figure 6). This failure was analysed and reported by Coxon (2000). His analysis indicated that the failure was circular in nature with no influence from structure, and resulted from recent heavy rainfall combining with the presence of a filled water sump at the toe of the slope.

A number of additional failures were evident in the pit at the start of the Stage 2 investigation (Figure 7). Air photos and memoranda indicate Moonbeam pit was flooded up to a level of approximately 332mRL (15-20m below surface). Saturating the pit walls by flooding the pit are believed to have caused most of the failures now evident in the pit (Feltus, 2009).

Figure 4. Cross section of geology of the Moonbeam Project (after Varvari, 2010).
Figure 5. Geology of the Kundana area and local geology of the Moonbeam Project (after Varvari, 2010).

Figure 6. Photo showing failure in Moonbeam Stage 1 open pit (after Coxon, 2000).
4.3 Geotechnical model

A simple model was developed for Moonbeam based on the geology, and inspection of the existing pit, and other similar open pits at Kundana. A cross section through the pit shown in Figure 8 summarises the main lithologies.

![Cross section sketch through Moonbeam showing existing Stage 1 pit (solid line), planned Stage 2 pit (dashed line), base of oxidation (red line) and top of fresh rock (blue line) (after Feltus, 2009).](image)

4.4 Slope stability analyses

4.4.1 Material strength properties

Reviews of Moonbeam Stage 2 reports show two differing sets of soil properties had been utilised by different authors. Varden (2006) derived values from back analyses of 7 small failures that had occurred in the Stage 1 pit.
reported by Heslop (2001). The material properties that were used in the final Moonbeam Stage 2 Open Pit design were presented and discussed by Feltus (2009); the stability modelling of the deposit used values derived from laboratory tests on materials associated with the Raleigh and Rubicon pits. Where a range of strengths existed, the lower limits of material strengths summarised in Table 1 were used in the model.

Table 1. Material strength properties used in the design of Moonbeam Stage 2.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Unit weight (kN/m$^3$)</th>
<th>Friction angle (°)</th>
<th>Cohesion (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxide (Sediments)</td>
<td>20</td>
<td>12</td>
<td>35</td>
</tr>
<tr>
<td>Oxide (Basalt)</td>
<td>20</td>
<td>15</td>
<td>45</td>
</tr>
<tr>
<td>Transition</td>
<td>23</td>
<td>28</td>
<td>50</td>
</tr>
<tr>
<td>Fresh (Basalt)</td>
<td>27</td>
<td>40</td>
<td>100</td>
</tr>
<tr>
<td>Fresh (Sediments)</td>
<td>27</td>
<td>40</td>
<td>90</td>
</tr>
</tbody>
</table>

The data obtained from oriented core recovered from four drill holes were used to ascertain defect orientations in the fresh rock and used for block stability assessments.

4.4.2 Results of analyses

Stability analyses were performed using the Rocscience program SLIDE™. Firstly, simulations were performed as back analyses of previous conditions known to cause failures in the pit walls. For example, the results of the analysis for rapid dewatering of the pit following its use for water storage. A Factor of Safety equal to 0.95 was obtained and confirmed the use of the parameters given above.

A number of deterministic simulations were carried out to assess the performance of different material types in the footwall (sediments) and hangingwall (basalt). The default analysis methods (Bishop Simplified and Janbu Simplified) were used for the analyses. Other parameters such as the number of slices, tolerance, and number of iterations were set to the default values (20, 0.005, 50). These runs tested the material properties used in the model. The model simulations and results were summarised by Feltus (2009).

In addition, the fresh rock stability for Stage 2 of the Moonbeam open pit was analysed by Varden (2006). Stability in the fresh rock zone was assumed to be controlled by structure due to the shallow depth of the pit. The assessment was based solely on kinematic considerations as neither the strength of the rock mass or the shear strength of specific structures had been determined. The majority of instabilities were expected to be wedge failures. Planar failure was not expected to be a common mode of failure. Toppling was a potential failure mode on the steeply dipping foliated planes when the strike of the wall was within the range of 20º to parallel to the foliation. The shallow dipping joints often form small wedges, which would amount to the size of scats if they failed.

4.5 Slope design

The design parameters that were used in Stage 1 of the Moonbeam Pit were modified to steeper batters and wider berms, while maintaining approximately the same overall slope angle. The steeper batters were considered easier to mine, while having a minimal detrimental effect on batter stability. The larger berms maintain the overall slope angle and create more area to catch potential batter scale failures and scats. The recommended design parameters that were used for the Moonbeam Stage 2 Pit are given in Table 2.
Table 2. Recommended slope design for Moonbeam Stage 2 (after Feltus, 2009).

<table>
<thead>
<tr>
<th>Material</th>
<th>Batter Height (m)</th>
<th>Batter angle (degrees)</th>
<th>Berm Width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxide (surface to 310mRL)</td>
<td>12</td>
<td>60</td>
<td>10</td>
</tr>
<tr>
<td>Fresh (310mRL to base of pit)</td>
<td>12</td>
<td>70</td>
<td>8</td>
</tr>
</tbody>
</table>

4.5.1 Observed performance and assessment

Moonbeam Stage 2 open pit commenced mining in February 2009 and was completed January 2010. The bottom of the Stage 2 pit was approximately 90m below surface when mining finished. During mining only two significant wall failures occurred; one in the small northern Christmas extension of the pit and another on the west wall of the main pit. Other small failures occurred but were not considered a hindrance to mine production.

The west wall (Basalt) performed well in both the oxide and fresh rock horizons. The only failure on this wall was structurally controlled by the Lucifer Fault, with the oxide interpretation being incorrect prior to design. The completed west wall can be seen in Figure 9. The east wall (Volcanioclastic Sediments) did not perform as well as the west wall. The structural complexity of this wall meant that the structures present contributed to severe damage to batter crests. Most of the failures were structurally induced but were small enough to be contained by the berms. The completed east wall can be seen in Figure 10. Both the North and South ends of the completed pit performed very well and no failures occurred. Christmas pit (the extension to the north of the main pit) had two failures. One large wall scale circular failure shown in Figure 11 with circular tension cracking, and one smaller failure that is believed to be structurally associated. Christmas was backfilled with waste material as the main pit progressed.
In summary, it is considered that the overall mine design proved to be successful and the strength parameters derived were appropriate. This was backed up with results using the SLIDE™ software. Some of the observed failures were caused by factors not included in the stability analyses such as greater depths of weathering than expected and spatial variation of faults. In the case of the west wall failure, a factor of safety equal to 0.95 was obtained for the actual geometry of the materials compared with 1.22 obtained for the original design assumptions.
The decision to use wider berms was vindicated in that the debris from bench scale failures was retained on the berms with no interruption to production. Regular visual inspections were conducted, and provided advanced warning of the failure which allowed for cautionary measures to be put in place so that personnel and equipment were never at risk.

5 Proposed methodology for design of small scale open pits

5.1 Process

The chart in Figure 12 shows a graphic representation of the sequence of events to follow when obtaining data to use in design. It follows the logical steps in order of data priority; i.e. data with the highest reliability to the project. These data sources in order are:

- Drill core with laboratory testing for material properties. Core should be oriented with structures logged and mapped.
- Existing pit in place – back analysis provides excellent material properties, outcropping and mapping of structures, location of water table.
- Drill core with no testing and un-oriented – RQD and FF available, rock mass characteristics visible, observed saprolitic conditions.
- Other open pits in close proximity, on same stratigraphic succession - back analysis will give a good estimation of the rock mass characteristics of the area, some laboratory testing may exist.
- Historical workings in the area – shafts, small scrapings, trenches will allow for back analysis of the near surface weathered material. Rock chips/waste material on dumps may give an indication of the nature of the hard rock, but very little useable data.

Figure 12. Designing small scale pits with limited geotechnical knowledge.
However, if no existing data sources are available in the area of the proposed open pit project, then the geotechnical engineer must evaluate the project and offer recommendations as to what is required to design a stable slope. Once the data have been reviewed, then slope stability assessments can be made; for example using SLIDETM for completely weathered materials and SWEDGE™ for structurally controlled failures in fresh or weathered rock.

5.2 Generalised soil strength properties

Twenty open pits across the Kalgoorlie Region were investigated to acquire the soil and rock strength properties that were utilised in their design. A total of 272 results were found covering the values for cohesion, friction angle and density for Oxide, Transition and Fresh Rock zones. It was noted whether these quantities were from laboratory testing, or were derived (i.e. from back analysis). The various values were then classified according to depth below surface, associated rock type and mining camp.

Generalised values for the materials associated with the Barrick Kalgoorlie leases that can be utilised are listed in Table 3. It is important that the geotechnical engineer does not use generalised values to design final pit slopes. Generalised values have been suggested to allow for a small test pit to be mined. This test pit is then to be evaluated, and from there the final pit is to be designed. Cohesion values for fresh rock were highly dependent on rock type. The range of these generalised values may be used in a probabilistic analysis of any proposed shallow pit. The resultant probabilistic values can be used to determine if initial design parameters are realistic and help determine if more testing is required.

Table 3. Generalised material properties.

<table>
<thead>
<tr>
<th>Material</th>
<th>Cohesion (kPa)</th>
<th>Friction Angle (°)</th>
<th>Density(t/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxide</td>
<td>0 -0/+50</td>
<td>25 -0/+10</td>
<td>1.8 -0/+0.2</td>
</tr>
<tr>
<td>Transition</td>
<td>50</td>
<td>30 -0/+5</td>
<td>2.3 -0/+0.2</td>
</tr>
<tr>
<td>Fresh</td>
<td>100</td>
<td>40 -5/+5</td>
<td>2.7 -0/+0.1</td>
</tr>
</tbody>
</table>

6 Concluding remarks

The case studies have shown that it is possible to design stable open pits that are small in scale with very little new data. Even with timing and other constraints in place, geotechnical engineers still have the ability to give a best possible estimation for a stable slope design. It is important to use all available data, whether this is from laboratory testing from materials associated with adjacent projects, or from back analysis of previously mined workings. If project specific information is not available, it is also important to find as many sources of data as possible to form the knowledge base. If drill core is available for the project then this should be used as first priority. However, if other information is available, such as an existing pit, this should also be used to provide increased data certainty.

It is planned to deepen a number of the pits that have formed the basis for these case studies. Accordingly, considerations are now being given as to how best to characterise the rock properties from exploration percussion drilling without dedicated geotechnical drilling. Research has been reported in the field of using percussive drill rigs to enable the characterisation of rock masses. This includes using penetration rates and torque to map large structures and to aid with RQD/FF analysis (e.g. Schunnesson 1996,1998). Point load testing of the rock chips has also been mentioned but has only been successful in the oil and gas industry to date (e.g. Meyers et al. 2004, 2005). These tools would be very helpful when drilling large amounts of RC to delineate ore reserves; however, they require a lot of work to enable them to be used in the area, and require a great deal of calibration at their set-up.
7 Acknowledgements
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8 References