Optimisation of the Eastern Pit Wall of the Superpit: An Example of a Staged Capital-Delivered Geotechnical Design to Increase Project Value

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Abstract

The Superpit is a maturing large open pit mine with the potential to maximise the economic return with steeper pit slopes. Business improvement studies in 2005 - 2006 posed the question “Is slope steepening possible for walls on the pit?” To answer this question a detailed slope optimisation project was commenced in 2006 and concluded in mid-2010. Three key themes of the project were:

1.) The use of a staged and targeted project approach that enabled a progressive capital spend aligned with the delivery of results and increasing geotechnical confidence.

2.) An increased geotechnical design confidence, which enabled steeper slopes to be considered, based on an increase in the resolution of the both the geological and geotechnical models, including the development of full 3D geotechnical domains.

3.) The establishment of a comprehensive Quantitative Risk Assessment model that enabled the increased risk profile arising from the optimised (steeper) slope design to be more readily comprehended by mine management and the company owners.

The project was managed and completed by in-house staff against a backdrop of unprecedented staff turnover and shortage in the Australian mining industry. At its completion the project delivered a greater benefit than previously thought through a reserve addition of 1.9MOz. (> AUD$900M estimated value) from an increase of 8° in the inter-ramp angle, and with a capital outlay of less than AUD$2M. The project is an excellent example of a staged capital-delivery geotechnical design process providing an optimum project return.

1 Introduction

The Superpit is currently one of the world’s largest producing gold mines and is located in the city of Kalgoorlie-Boulder in Western Australia. The mine, which is owned and operated by the Kalgoorlie Consolidated Gold Mines JV (owned 50% each by Barrick Gold and Newmont), is extracting gold ore from the famous Golden Mile deposit that has produced more than 57MOz. in over 100 years of production. Although mining of the Golden Mile was largely through underground means, since 1989 the operation of the Fimiston pit (Superpit) has sought to extract the remnant haloes surrounding the bonanza grade lodes of the Golden Mile.

The current Superpit is approximately 3.5kms long, 1.8kms in width and up to 550m depth. The final pit will approach 750m depth and there is potential for additional underground mining to occur. Mining of the pit has occurred through conventional drill-blast and load-haul means using diesel-powered hydraulic shovels. The deposit comprises two main lodes, the eastern and western lodes and this has resulted in the final pit having a pronounced en-echelon shape. Internally, the pit is divided into three major areas; Trafalgar, Chaffers and Golden Pike, which have been mined at various stages during the life of the mine.

The Golden Mile deposit is hosted within 2.7Ga (Archean) aged meta-dolerites and meta-basalts that have experienced multiple episodes of tectonism/metamorphism. The host rocks exhibit a high rock mass strength and the resultant pit wall deformation is typically quite low. Wall stability is principally controlled by the 3D
structural geology architecture. Prior to the east wall optimisation project being initiated the slope design criteria were applied uniformly across each of the major walls of the pit as summarised in Table 1. This approach worked well for the pit and by 2006 long term pit wall performance was very good.

Table 1. Summary of pit slope design criteria applied (planned) for key cutbacks within the Fimiston (Superpit) pit prior to commencement of the wall optimisation project.

<table>
<thead>
<tr>
<th>Pit Area</th>
<th>Wall Location</th>
<th>Batter Height (m)</th>
<th>Batter Angle (°)</th>
<th>Berm Width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trafalgar</td>
<td>East</td>
<td>30 (3 x 10)</td>
<td>65</td>
<td>10</td>
</tr>
<tr>
<td>Chaffers</td>
<td>East</td>
<td>30 (3 x 10)</td>
<td>65</td>
<td>10</td>
</tr>
<tr>
<td>Chaffers</td>
<td>West</td>
<td>30 (3 x 10)</td>
<td>75</td>
<td>10</td>
</tr>
<tr>
<td>Golden Pike</td>
<td>West</td>
<td>30 (3 x 10)</td>
<td>75</td>
<td>10</td>
</tr>
</tbody>
</table>

1.1 Continuous improvement philosophy

Both owners of the Superpit maintain a strong continuous improvement culture. In 2005 and 2006 this was enacted at site through Operational Review Team (ORT) meetings during which the opportunities to steepen the eastern pit wall were considered. Amongst other things the review team considered the following anecdotal evidence to support wall steepening;

1.) The previous fifteen years of slope performance was exceptionally good and characterised by limited failure, stable pit walls and was relatively easily implemented at an operational level. It was also increasingly recognised that the dominant failure mechanisms were by discrete structures rather than through rock mass modes.

2.) Improvements to the geotechnical model through increased resolution, coupled with rigorous implementation in the field, could likely support a steeper wall design.

Following the ORT meetings the wall optimisation project was implemented with the following aims;

a.) To add value to the mining operation through an increase in ore reserve from wall steepening. Such an increase would also deliver an increased mine life adding additional benefit to the community, which remains a significant stakeholder in the mine’s future.

b.) To achieve the reserve increase through wall steepening whilst maintaining acceptable risk tolerance.

c.) To ensure that all wall designs conformed with applicable regulatory criteria, were completed with due diligence and using best industry practice.

The project initially set out to examine the east wall of the pit (which is adjacent to the Fimiston Mill). This was because this side of the pit would i.) yield the most significant return from being steepened and ii.) be more likely to be accepted by external stakeholders as it was on the side of the pit that was opposite to the wall that was adjacent to the town.

2 Project methodology and execution

Due to the complex scale of the project, as well as corporate owner requirements and the strategic importance of the outcomes a phased (staged) approach, similar to that proposed by Steffen (1997) and illustrated in Figure 1, was adopted. One of the principle drivers for this was the relatively tight supply of both capital and technical resources. Key characteristics of the staged approach are;
1.) That the geotechnical design is considered as a phased delivery in which specific project stages correlate with reserve classifications in line with geotechnical design confidence.

2.) Geotechnical work is considered as an ongoing process that can be undertaken as part of the normal mine planning operation.

3.) That the different phases require different levels of detail and that a high level feasibility study is not required to initiate the project.

4.) That the staged approach would correlate to normal reserve standards required by owner stock exchanges for the declaration of mining reserves.

Steffen’s staged project delivery approach adopts three classification stages of geotechnical confidence that can be applied to a mine reserve (Table 2). Using these stages the project advanced the geotechnical design confidence for a steeper slope design from Possible through to Proven. In this manner both capital and technical resources were not over-committed early in the project. The approach also aligned closely with the ‘stage-gate’ process (Fig. 2) of Newmont (one of KCGM’s owners) whereby projects are advanced with incremental capital and results outcomes. The benefit of these approaches is that it allows large capital projects to be progressed primarily within the typical constraints of a large mining operation (limited capital and human resources).

The Fimiston wall optimisation project was completed in two main phases:

Phase 1: - Addressed both Phase 1A & 1B of the Steffen (1997) equivalent process through development of a pre-feasibility level case that indicated the potential for a +800,000 Oz. reserve addition was possible. This stage was completed firstly with consideration of current inputs (Fig. 1) that then expanded to preliminary geotechnical analysis including field trials of proposed steeper batter configurations. These elements of the project were largely completed in-house using available staff and data and with no capital outlay (e.g. Beer & Morrongiello, 2007). The reserve addition was classified as Probable (e.g. Table 2) and was derived from the commencement of a trial of the new 70° batter face angle. In terms of the overall project, this stage was important in establishing the concept and acceptance to proceed (with capital outlay) to the next stage which would endorse the benefit to the Proven level of confidence.

Phase 2:- Equivalent to Phase 2 of Steffen (1997) this confirmed the outcomes of Phase 1A & 1B such that the reserve addition was endorsed to a Proven level. This phase required the completion of a fully detailed geotechnical study (Fig. 1) and at its completion also confirmed the potential for additional steepening from the 70° batter face angle to a 75° version. Continued endorsement, through the detailed design analysis undertaken in Phase 2, confirmed a final 75° batter face angle-based slope delivering a reserve addition of >1.9M Oz.

The approach that was adopted allowed the project to develop within the time constraints of mining exposure. An important data source for the new slope design was the implementation of extended field trials of the steeper slope design criteria. Under this project development process these could be adequately accounted for without the early over-commitment of capital resources. The functional inputs used to execute the new slope designs also largely remained the same and were accounted for by using those applied to the existing mining operation.

The importance of Phase 1 cannot be emphasised enough. In effect this preliminary stage allowed a significant advancement in confidence that the slope could be successfully steepened through the application of re-design analyses using current data sets and field trials of steeper configurations. Both these were able to be completed without any capital being required and within the ongoing operating environment of the pit.

The completion of Phase 2 was greatly facilitated through the establishment of:

1.) A project steering committee comprising the project manger (representing the operating company and the project execution team) and geotechnical representatives from each of the JV owners (providing additional technical and capital funding direction).
An established review system whereby all stages of the project were technically reviewed using specialist reviewers, and the overall project advancement regularly reviewed using a review board comprising two high-level international review consultants. This review board was established at the early stages of project inception.

### Table 2. Summary of geotechnical confidence classifications proposed by Steffen (1997) to be applied to mining reserves.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Possible</td>
<td>Application of typical slope angles based on previous experience in similar rocks; quantification is on the basis of rockmass classifications and inference of the geological conditions.</td>
</tr>
<tr>
<td>Probable</td>
<td>Design is based on information that allows a reasonable assumption of the continuity of the stratigraphic and lithological units. Major joint sets are identified and some rock testing has been undertaken.</td>
</tr>
<tr>
<td>Proven</td>
<td>Continuity of geological elements is confirmed with adequate intersections, detailed structural mapping of the fabric is implied, strength testing completed to a level to enable reliable statistical interpretations to occur. The design can be carried out to a confidence of 85%.</td>
</tr>
</tbody>
</table>

3. **Completion of the optimised geotechnical design – Phase 2**

Following the completion of Phase 1 whereby the potential to add significant mining reserve was identified and quantified to a reasonable level of confidence it was necessary to undertake a formal detailed geotechnical design project to endorse the steeper slope configuration to the highest level of confidence, Proven. The detailed design project also had the aim of establishing a formal risk model for the pit from which the revised, and any subsequent design changes could be benchmarked in terms of geotechnical risk on the operations. A design methodology (process) broadly following the sequence of Figure 2.1 in Read et al (2009) is adopted at KCGM. Key components of this process that contributed to the success of the east wall optimisation project were;

1.) Detailed 3D structural geological model
2.) Construction of 3D geotechnical domains
3.) Extensive field trials of proposed new batter-berm configurations.
4.) Numerical modelling and quantitative risk assessment modelling

#### 3.1 Detailed 3D structural geology model

The 3D structural geological model was constructed using face mapping and diamond drilling data. A key component of the Phase 2 capital spend was a program of targeted oriented diamond core drilling to locate structural intercepts behind the potential final steepened wall. As many of the berms within the Fimiston pit are inaccessible due to relict underground workings a photogrammetry process was established to expand and increase the face mapping data coverage. Both the drillhole and photogrammetric data were calibrated against ‘on-the-floor’ face mapping that was completed on key faces.

The resultant 3D model was constructed as a series of wireframes using Vulcan™ design software, which were then intercepted with the pit wall shells/designs (Fig. 3). The modelling identified a number of previously unknown large structures that would ultimately require additional assessment. The majority of major structures
run north-south through the pit, however examples of moderate-west dipping structures were also encountered. Major fault intercepts in drill core were identified and tagged and used to build the larger structure model.

Four significant structural sets, using an orientation basis, were determined present in the Fimiston pit. Modelling of the structures identified faults that were i.) Major (defined as those with a strike greater than 1000m) and ii.) Minor (defined as those with a strike less than 1000m). Pre-existing modelled faults were re-modelled using updated datasets and new structures added. At completion more than 50 discrete modelled surfaces were identified.

Figure 1. Summary of the project development process applied to the Fimiston east wall optimisation project with comparison to Steffen (1997) and Newmont stage-gate project delivery processes.
Figure 2. Detailed schematic of Newmont ‘Stage-Gate’ process of capital and project delivery from which a business case is conceived, assessed and modelled/approved through to execution in a mining operation.

Figure 3. Aerial photo of KCGM Superpit (July, 2010) showing the major structure intercepts with the pit walls.
3.2 3D geotechnical domains

Geotechnical domain selection was based principally on two factors, i.) the prevailing rock type and ii.) boundaries imposed by the major structures thus considering the domains as effectively fault blocks. The reason for this is that in consideration of the complex structural development of the region that major faulting (established during tectonism) will be the single most influential control on the geometry of both minor structures and rock fabric. The development of 3D domains utilising inter-linking major structures in effect will focus the ongoing data reduction to identify any changes in rock defect condition, even those that are relatively subtle, so that appropriate design modifications will be optimal.

The domains were constructed using the Boolean 3D solid wireframe process in Vulcan™ and the major wireframe surfaces that had been constructed (Fig.4). The domains were then used to spatially select the geotechnical fabric data that would be subsequently reduced. Spatial variations within each domain were assessed to determine the validity of the boundaries, and in one case this resulted in additional spatial subdivision of the original domain.

Figure 4. Summary graphic showing the resultant 3D geotechnical domains intersected onto the ultimate Fimiston pit shell.

3.3 Field trials

An important component of the optimisation process was the completion of field trials of the proposed steeper design criteria. The field trials allowed the steeper configuration to be progressively implemented into the operation cycle (Fig. 5) and provided confirmation of the design assumptions to be made. Initially, a 70° BFA configuration was trialled for the majority of the Trafalgar and Chaffers cutbacks for which steepening was being considered. The ongoing success of the 70° configuration led to a further change to 75° during the middle of the project. During the field trials key elements of the drill and blast implementation were able to be further evaluated and, in some cases, modified.

Key outcomes from the field trial that substantially impacted (and benefited) the project included;

1.) The increased confidence from actually seeing the steepened slope configuration and knowing that it could be successfully implemented. The berm/crest retention performance within the trialled areas was measured (using photogrammetry) and used to compare the performance of the field trials overall.
2.) Endorsement of an appropriate single-stage pre-splitting configuration that addressed concerns over remnant ‘lips’ and excessive toe, both of which arose when a double-stage pre-split configuration was used.

3.) The ability to undertake rockfall risk modelling on the steepened section of slope that led to recalibration of the rockfall model and endorsement of the $75^\circ$ batter configuration as being optimal (Hewson & Corskie, 2009). The rockfall modelling showed that for a given berm width an inter-ramp slope defined by a $75^\circ$ batter angle was most optimal in terms of reducing the distance that rocks would fall down such a slope.

![Figure 5. Summary graphic showing the progress sequence of successive batter steepening and some example pictures of final achieved eastern pit wall. The 75° trial configuration was formally commenced in late 2009](image)

### 3.4 Numerical modelling and quantitative risk assessment

The proposed steeper slope configurations for the pit were comprehensively assessed using 2D numerical modelling methods. A 2D approach was considered sufficient because:

- a.) The elongate geometry of the final pit wall
- b.) The ultimate pit presents only a limited section of full height slope with the remaining lateral extent being buttressed by ramps and step-out areas.
- c.) Failure mechanisms are predominantly associated with defect sets that dip parallel to the strike of the planned wall thus reducing apparent dip effects significantly.

Models were constructed for a set of section lines, selected to investigate key aspects of the slope geometry, using the geotechnical domains, major structures and rock mass properties. Nine base case modelling scenarios were modelled (Table 3) to assess the sensitivity to changes in i.) material properties (3 scenarios) and ii.) groundwater conditions (3 cases). Both of these represented potential key unknowns in the slope modelling and by modelling the sensitivity of them could be determined and a decision made as to whether to investigate (data...
collection) that are further. In particular, the groundwater condition was not fully confirmed at the start of the project but subsequent deep piezometers were installed.

The use of scenarios was expanded through conducting a fault-tree workshop to derive additional areas of uncertainty for the geotechnical design. These uncertainties were modelled into a Quantitative Risk Assessment model using a response-surface method (e.g. Steffen & Contreras, 2006; Steffen et al, 2008). The response-surface approach is similar to a point-estimation method but the continuous response surface that is generated will ensure a smoother outcome curve is derived from the monte-carlo sampling process. The five inputs considered were, i.) rockmass properties (as per the original material properties), ii.) groundwater, iii.) D (disturbance) factor applied to the rockmass assessments, iv.) fault properties and v.) position uncertainty for one of the major underlying faults.

Table 3. Summary of the nine numerical modelling scenarios applied to each section line modelled; the two main uncertainties (or influences on slope stability) were groundwater and material properties applied in the model.

<table>
<thead>
<tr>
<th>Groundwater Conditions</th>
<th>Material Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>No pore pressure (dry)</td>
<td>Upper Bound</td>
</tr>
<tr>
<td></td>
<td>Average</td>
</tr>
<tr>
<td></td>
<td>Lower Bound</td>
</tr>
<tr>
<td>50% Pore Pressure</td>
<td>Upper Bound</td>
</tr>
<tr>
<td></td>
<td>Average</td>
</tr>
<tr>
<td></td>
<td>Lower Bound</td>
</tr>
<tr>
<td>100% Pore Pressure</td>
<td>Upper Bound</td>
</tr>
<tr>
<td></td>
<td>Average</td>
</tr>
<tr>
<td></td>
<td>Lower Bound</td>
</tr>
</tbody>
</table>

The main area of potential risk for the steepened pit slope was considered to be at the inter-ramp scale with either a planar or wedge failure initiated on semi-major structures. As such both global slope and inter-ramp scale modelling was applied to generating the response surfaces. Application of the risk modelling process indicated the following key outcomes;

1.) The final probability of failure for the steepened pit wall was <0.2%.

2.) Both rockmass strength and groundwater were the predominant contributors to variance (Fig. 6); the effect of the underlying fault was very minimal.

3.) The consequence tree analysis confirmed a strong reliance on maintaining good monitoring systems and evacuation process was required to reduce the risk of an adverse outcome in the event that a slope failure event might occur (see also below).

4.) The resultant risk outcome, both for a safety (personnel) and economic (production) loss, were for the steepened slope within acceptable limits. Acceptable limits have been set as equivalent to those imposed by normal air travel.
4 Final project outcomes and execution strategy

The results of the optimisation project are summarised in Table 4, with the final pit slope design steepened by up to 7.5° at the inter-ramp scale. This was undertaken progressively by first commencing with a 70° batter configuration for both the Chaffers and Trafalgar cutbacks. With the success of the 70° configuration this was subsequently expanded to a 75° angle in the Trafalgar cutback resulting in a final increase of approximately 4° in overall slope angle for the eastern wall. This steepening of the eastern wall resulted in the addition of 1.9MOz. to the reserve and was a significant contributor to the mine life extending from 2017 to 2021. At the community and owner level this is a tangible benefit of the wall optimisation project.

An additional aim of the project was to continue efforts to optimise the pit slope. This included assessing the potential to steepen the slope further again, which in this case would imply an 80° batter configuration in the Trafalgar cutback.

![Figure 6. Summary tornado graph illustrating the contribution to variance made by the five QRA model variables. Rockmass and groundwater inputs are the largest contributors to variance in the slope design.](image)

4.1 Risk assessment and confidence of design outcomes

A risk assessment of the design outcomes was undertaken and the confidence of the new design criteria assessed. The results of the risk assessment were used to assess any outstanding areas of uncertainty in the model and the impact that these would have on the ability of the operation to execute the new design. Areas of assessed potential uncertainty in the models included;

- Adversely oriented rock fabric/structures (inter-ramp scale) being encountered.
- Adverse hydrogeology conditions being encountered within the slope.
- The potential for limited inter-ramp scale instability arising from a non-identified major structure.
- Loss of critical personnel leading to an inability to properly maintain the slope management plan.
The results of the risk assessment align closely with assessment of the geotechnical design confidence. This indicates that areas that should be focussed on going forward are those at the inter-ramp scale where the presence of a previously unidentified structure could initiate an adverse slope condition. Two areas with relatively low design confidence (high likelihood of unknowns) and therefore increased risk to achieving the design were identified and have been addressed in subsequent work programs that in effect will form a pseudo-Phase 3 to the project.

Table 4. Summary of slope design outcomes from optimisation project (compare with Table 1). The west wall parameters (Golden Pike) are also listed for comparison. SH – Stack Height; BFA – Batter Face Angle; BW – Berm Width.

<table>
<thead>
<tr>
<th>Design Case</th>
<th>Location</th>
<th>SH (m)</th>
<th>BFA (°)</th>
<th>BW (m)</th>
<th>Inter-ramp Angle (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Optimisation</td>
<td>Trafalgar &amp; Chaffers (east)</td>
<td>30</td>
<td>65</td>
<td>10</td>
<td>51.4</td>
</tr>
<tr>
<td>Phase 1 (70°)</td>
<td>Trafalgar &amp; Chaffers (east)</td>
<td>30</td>
<td>70</td>
<td>10</td>
<td>55.1</td>
</tr>
<tr>
<td>Phase 2 (75°)</td>
<td>Trafalgar (east)</td>
<td>30</td>
<td>75</td>
<td>10</td>
<td>59°</td>
</tr>
<tr>
<td>Golden Pike West</td>
<td>West</td>
<td>30</td>
<td>75</td>
<td>10</td>
<td>59°</td>
</tr>
</tbody>
</table>

4.2 Design implementation (execution) strategy

Outcomes from both the hazard/risk and design confidence assessment help to drive the development of an appropriate implementation plan that will determine the resources required to successfully capture the benefits of the slope steepening project. This has been captured in gantt chart form in MS Project so as to track the timing and delivery of such resources. Key components of the implementation plan include:

1.) Appropriate slope monitoring resources are available during the life of the steeper slope (this is driven as well from the consequence trees in the QRA modelling whereby improved slope monitoring response time is a significant driver to reducing risk).

2.) Establish a rigorous program of structural geology mapping and model update, utilising the photogrammetry and face mapping data collections, to i.) identify and ii.) model current and emerging structures in the eastern pit wall.

3.) Implement a blasting optimisation project, including routine face quality assessments, to ensure that wall damage and other departures from the design that may arise due to blasting are identified and addressed.

4.) Installation of deep level vibrating wire piezometers to i.) confirm and ii.) monitor the east wall groundwater conditions.

5.) Attention to appropriate human resource (HR) strategies to attract and retain key technical staff. This has included the development of a detailed graduate geotechnical engineer program that aims to complete vocational mining geomechanics training for young engineers new to the mining industry.

5 Conclusions

This project was established to geotechnically optimise the eastern pit wall of the Fimiston (Superpit) pit through progressive steepening of the batter face from an angle that did not undercut the incipient foliation to one that
The new overall slope angle that arose was 4° steeper, and 7.5° steeper in the inter-ramp scale. The most significant outcome from the project was an >AUD$900M value addition through a 1.9MOz. increase to the LOM reserve. Key components of this project that led to this success include;

1.) The use of a phased approach to project schedule and particularly capital delivery. This was aligned with the progressive delivery of results and incremental increases in geotechnical confidence. It was also aligned with a similar process of one of the owners (Newmont).

2.) Point 1 was strongly supported through establishing, early in the project, in-field trials of the proposed steeper configuration. These are considered pivotal in helping to establish acceptance of the revised design and to improve the confidence in the review team that the designs could be successfully implemented. The field trials also complemented the pre-existing 20+ years of successful mining performance.

3.) Targeted structural and geotechnical model building to improve the resolution of pre-existing datasets that supported more accurate and focussed geotechnical outcomes.

4.) Scenario modelling of data unknowns and assessment of the impact of these with the quantitative risk model. In this manner limited resources were able to be focussed on areas of the model/design process that could have the greatest potential impact on the final outcomes. In effect this continued the targeted approach established for many parts of the project.

5.) Development of a rigorous implementation strategy to support the capture of the project benefits. Hazard risk assessment, consequence trees and an assessment of geotechnical confidence for each of the pit design elements guided the development of the strategy.

6 Acknowledgements

The work of the project steering committee, which included the authors and Bob Sharon, in overseeing the technical direction of the project, and periodic review and guidance from Pete Stacey and Oskar Steffen is gratefully acknowledged. The authors would like to thank KCGM, and its respective owners (Barrick Gold and Newmont) for permission to publish this paper.

7 References


