Keynote Paper:

Slope Design in Large Open Pit Mines

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Abstract

With easily accessible mineral resources becoming more scarce, increasing commodity prices, and improved production capabilities, our mines are extending to greater and greater depths. In open pit mining this leads to much larger slopes than have previously been considered or implemented, and which are certainly beyond the experience of the majority of miners and geotechnical practitioners. At these increased heights the risk of slope failure becomes greater, dependent upon the imposed design, and makes us question whether the analytical assumptions previously used on lesser slope heights are still valid.

This paper discusses some of the differences, and similarities, between the design of “typical” and “larger” open pit slopes and uses the design of the south wall pushback at Bingham Canyon Mine to emphasise some of the important design elements.

1 Introduction

In design of mine slopes there are few differences between those for shallower excavations and those for deep mines (greater than 500m). In all cases, the need for a comprehensive knowledge of the following items remains paramount:

- the structural geology of the ore body and surrounding country rock,
- the properties of the soils, rocks and discontinuities,
- the site hydrogeology and hydrology, and
- the stresses which will be imposed upon the excavation as a function of the proposed mining.

The key differences relate to the scale of the mine slopes themselves, both in terms of wall height and the magnitudes of the imposed stresses, and the time that large slopes are required to remain standing.

The term large open pit slope implies larger failures to the reader, and likewise greater impacts upon safety and production at a given operation. There can also be a significant impact on project value during mining as a function of the need for slope remediation, following failure, and localised wall flattening. Our tendency is to manage these potential impacts by design, with selection of more stringent design acceptance criteria, or conservatism, to counteract uncertainties in our data and analytical abilities, and the consequences of slope failure.

The final selection of a slope design depends on our confidence in predicting the slope heights and angles to be imposed, our ability to effectively communicate the risks and opportunities presented by the design, and a mine’s selected criterion for acceptance of a given slope geometry for implementation. These criteria vary dependent upon an individual mine’s, or a corporation’s, appetite for risk.

This paper presents a discussion of the slope design process employed as part of the south wall pushback design at Rio Tinto’s Kennecott Utah Copper, Bingham Canyon Mine.
2 The slope design process

The slope design process has been described in many texts, and is summarised in Figure 1. Much as this process flow is similar for the design of all mine slopes, there are relatively few precedents for the behaviour of mined slopes where height exceeds 500m. As such there is relatively increased uncertainty in the prediction of ground performance in large slopes with factors such as high stress and strain, intact rock breakage, and time dependency having significant parts to play in the prediction of slope stability and the management of the risks associated with a given design.

关键在于任何设计是数据输入到我们的模型以及评估斜坡稳定性的分析方法。所有斜坡设计都存在一个风险因素，这需要在项目审批过程中进行评估和考虑。一旦决定并开始挖掘，设计实施将是确保斜坡安全的下一个重大步骤。这些问题在以下各节中讨论，特别是在比格顿峡谷矿山南墙扩建研究的背景下。

Figure 1. Slope design process. (Source: Read and Stacey 2009).

Key in any design is the quality of data inputs to our models and the analytical methods employed to assess stability of the slopes. All slope designs present an element of risk to an operation and this matter needs to be assessed and considered during the project approval process. Once a decision is made and excavations commence, design implementation plays the next major step in security of our slopes. These matters are discussed in the following sections in the context of the Bingham Canyon Mine south wall expansion study.
3 Bingham Canyon Mine

A detailed overview of the Bingham Canyon Mine is not possible within the scope of this paper, but some of the main points of importance in relation to the mine, and the south wall pushback are as follows:

- The Bingham Canyon open pit mine has been in operation since 1906, with underground mining having commenced in 1863. At the time of writing, the mine is over 3km wide at the crest and some 900m deep.

- The mine is excavated into a sequence of folded and faulted, sedimentary quartzites and lesser limestone beds and lenses. A monzonite intrusive was passively intruded into the sediments and comprises the bulk of the mineralised Bingham Stock. The monzonite itself was intruded along its north-western boundary by a quartz monzonite porphyry ‘dike’ which hosts the bulk of higher grade mineralization. A schematic section of the mine and underlying ore zones is shown as Figure 2.

- The open pit is situated within the north dipping southern limb of the west-north-westerly trending Bingham Syncline. On the south and southwest side of the pit are a series of NNE-trending faults and fissures. On the west side of the pit are a series of more northerly trending faults, some of which show nearly horizontal left-lateral movement that appears to post-date mineralization. Less abundant, but more significant in terms of displacement, are a set of northwest trending faults.

- Groundwater flow at the mine is typically within broken zones along fold axes, along lithologic contacts and bedding planes, within blast affected rock near the pit wall, and within historic underground workings. Hornfels-altered sediments, clay-filled faults, and limestone units impede flow. Groundwater levels have been reduced in the immediate vicinity of the pit, due to mine development below the natural groundwater levels, pumping of underground workings, installation of horizontal drains and drainage galleries, and pumping wells. Pore pressures in most pit slope sectors are elevated, although generally...
well controlled, and show a vertical downward gradient towards the pit. Extensive hydraulic testing indicates that the wall rocks mostly have moderate to low hydraulic conductivity.

- There are four major sets of underground mine workings in the Bingham District all of which provide zones of artificially elevated water flow and storage. The Highland Boy Drainage Gallery has been developed in the north west corner of the pit to reduce water pressures in the wall in this region, and allow localised slope steepening.

3.1 The south wall pushback

The life of mine (LOM) plan for Bingham Canyon Mine extends operations to 2019. Work on the south wall pushback has been undertaken, indicating a further extension of the mine life to 2028. The approximate extent of the south wall pushback is shown in Figure 3. This pushback represents a further deepening of the pit floor from the current level (4390ft\(^1\)) through the current LOM floor level of 3790ft.

![Figure 3. Geometry and geology of the south wall pushback.](image)

The south wall pushback project comprises a mine extension of about 300m and deepening of the mine by a further 30 to 100 metres. The shape of the pit as part of this project will get wider on the southeast side and deeper at the base.

4 Data quality and quantity

Large open pit mines, as a function of their size, have been in operation for long periods of time. Provided records have been kept, a long mine life yields a large amount of data in terms of slope performance and previous failure history. This can be invaluable in terms of experiential learning of what design slope angles can be achieved within similar ground, but also for back-analysis for rock mass strength estimation and derivation of parameters for forward analysis of future cut-backs.

For existing mines, slope performance information, pre-feasibility and feasibility investigation and analytical data should be available from the initial mining studies as well as from subsequent push-back designs. This is a

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\(^1\) All elevations within the mine are quoted in imperial units, rather than SI. This is to avoid any confusion given that the site works in imperial units.
great benefit but can also pose analytical difficulties given that different generations of ground investigation may have collected different types of data. They also may have collected the same data types under different regimes and can be inconsistent. Knowledge of the methodologies used in each separate phase of data collection is needed to ensure that statistical work undertaken on data collected considers only like-data sets. Otherwise analytical outcomes can become biased, potentially leading to incorrect outcomes for subsequent analysis.

The Bingham Canyon geological, geotechnical and hydrogeological data sets are extensive and many years of slope performance leanings are available from both documentation and from the experiences of long serving staff members and consultants. Some data inconsistencies were identified during the south wall studies. One of these related to rock quality data, with early drilling programs having been undertaken before formal introduction of the RQD concept (Deere 1964). This early drilling data was lumped into broad bins of “rock quality” rather than quoting actual values. Given that the majority of current rock mass characterisation methods rely on RQD values, these “bins” of rock mass character data were only of limited use and, as such, had to be excluded from further analysis.

Another issue arose in relation to core quality. Early drilling programs had used single and double tube methods compared to more appropriate, triple tube methods which are best applied to recovery of core for geotechnical logging purposes. Rock mass characterisation routines have typically been developed at site on the basis of measured slope performance relative to RQD values from recovered core. At Bingham Canyon it was found that new and old holes drilled adjacent to each other showed dramatically different RQD values, on the basis of the drilling methods employed, as well as improved core handling practices. This needed to be accounted for in RQD modelling, and as such, some data had to be normalised.

The importance of core logging standards, standardised data collection and storage methodologies and training of logging staff cannot be stressed strongly enough in relation to long term mine geotechnical projects, and the need for consistent, good quality data for future analysis.

4.1 Failure back-analysis

To supplement discrete data from geotechnical testing, the use of slope performance data from displacement monitoring and failure back-analysis is essential. It is really the only way to arrive at a true rock mass strength, particularly in large slopes where analytical precedents are often lacking. In any failure back-analysis, the key assumption relates to the mode of failure which gave rise to the ground movements observed and measured. Within this, is the measurement, or assumption, of water pressures within the slope at the time of failure. Where large mass movements occur in a well known geological environment, following a triggering event (heavy rainfall, major adjacent blast event, etc) determination of the mode of slope failure can be straight-forward. However where ground movements are occurring over a large slope area, the geology is complex and access for drilling has been difficult, many assumptions are often made in an attempt to tie all of the observed movements into a single all encompassing mechanism prior to analysis. These assumptions can easily be incorrect.

In the Bingham Canyon south wall, ground movements have been observed/monitored over a prolonged time period. Geological structures were identified to explain ground movements in the upper, sedimentary slope sequence, although interpretation was more difficult in the lower igneous slope section. Additional drilling was undertaken and geological interpretation carried out, which inferred that an extension of the structures into the igneous lithologies did not exist. However the results of various in-ground monitoring systems indicated zones of disturbance within the igneous rocks which broadly concurred with an extension of the overlying structures. This interpretation led to formulation of a single, although complex, mode of slope movement for further analysis.
5 Slope stability analysis

For large slopes, as for those of lesser height, three stages of slope design analysis are required, namely

1. Bench scale,
2. Inter-ramp scale, and
3. Overall slope scale.

The analysis undertaken for 1 and 2 above would not vary markedly between large and shallower slopes, although the same cannot be said for cost benefit approaches to design and overall slope stability analysis.

For the stability analysis of large slopes a range of methodologies are typically employed with complexity increasing with the level of study, from order of magnitude, through feasibility to detailed design. Limit equilibrium methods can reasonably be employed at all study levels, although the complexity and detail of the geological, materials property and hydrogeological data inputs will increase as a function of both volumes of data available relative to study stage. Numerical models, likewise, can increase in complexity and are more typically used in later levels of study and for larger slopes.

In any slope stability analysis, the key feature is to understand the mode of failure relative to the conditions and character of the ground under assessment. Simply creating a numerical model of the geology, inputting geotechnical and hydrogeological parameters and seeing what comes out of it is like shooting in the dark!

A model is, by definition a representation of something, either as a physical object which is usually smaller than the real object, or as a simple description of the object which might be used in calculations. As such it is a simplification of the real thing. The only known fact about a typical model is that it is not completely correct. The amount of model simplification required is dependent upon the scale of the slope being analysed, the level of detail within the model and the capacity of the computer system to run large models. This has been one of the focal points of the Large Open Pit (LOP) research project.

For the Bingham Canyon south wall pushback 2D slices were cut through locations deemed critical in terms of slope stability, as a function of the presence of adverse structural orientations, low material strength zones and/or areas of known high water pressure. These needed to be simplified for use in 2D analytical packages, with a focus on retaining the broad distribution of the component geological and geotechnical materials and major geological structures and fabric orientations. Pore pressure distributions models were then developed for the same sections such that both transient and final pore pressures could be developed for each stage of mining and slope stability assessed. Each section was analysed using limit equilibrium analysis as a first pass as well as with FLAC.

Given concerns over the potential behaviour of the rock mass at the proposed slope heights a variety of rock mass strength models were considered – a Mohr-Coulomb constitutive model using parameters derived from Call & Nicholas’s method of estimation and the Hoek-Brown GSI method. The differences in the rock mass strength estimates achieved for the various slope materials were found to be immaterial providing confidence in the approaches undertaken.

A range of final and interim pit shells were developed and each assessed in terms of Probability of Failure (PoF) and Factor of Safety (FoS), using both limit equilibrium methods and FLAC.

During analysis it was found that certain sections did not achieve the required acceptance criteria and slope geometries needed to be modified. 2D models of specific slopes sections were developed at different overall slopes and FoS assessed for each. An example of the results gained for a single cross section is shown in Figure 4. This methodology was used to identify which overall slope angle should be considered in modifying the pit shells prior to more detailed analysis. In this way a final pit shell and design was developed which achieved the identified slope design acceptance criterion.
In any major slope analysis, consideration should be made to the need for 3D analysis vs. 2D. In broadly circular pits, like Bingham Canyon, it was felt that 2D cross sectional analysis, as a function of the lack of lateral constraint on the model, could provide pessimistic geotechnical outcomes. For this reason, 3D models were developed, although due to model size further reductions in geological complexity were necessary. In addition, all 2D cross-sections were extruded laterally to provide an element of confinement (referred to as 2.5D analysis). It was found that the 3D analysis did not identify significantly different outcomes from the detailed 2D analyses, providing confidence in the approach taken.

Figure 4. Sensitivity of FoS to overall slope angle.

6 Risk based design

Key to any design is identification and communication of the slope design acceptance criterion. A range of typical criteria for mine slopes are presented in Table 1. These criteria are well understood by the geotechnical community, but how well have we educated our mine management on what exactly does a Factor of Safety of 1.30 mean compared to 1.20?

Table 1. Typical slope failure design criteria (Source: Read and Stacey 2009).

<table>
<thead>
<tr>
<th>Slope scale</th>
<th>Consequences of failure</th>
<th>Acceptance criteria*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FoS (min) (static)</td>
<td>FoS (min) (dynamic)</td>
</tr>
<tr>
<td>Bench</td>
<td>Low–high</td>
<td>1.1</td>
</tr>
<tr>
<td>Inter-ramp</td>
<td>Low</td>
<td>1.15–1.2</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>1.2–1.3</td>
</tr>
<tr>
<td>Overall</td>
<td>Low</td>
<td>1.2–1.3</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>1.3–1.5</td>
</tr>
</tbody>
</table>

*a: Needs to meet all acceptance criteria
b: Semi-quantitatively evaluated, see Figure 13.9
Given the critical impact of slope design on operational safety, mine production and overall project value, our confidence in our final design needs to be as high as is reasonably practicable. This can only be gained by constructively challenging our models by use of teams of quality, experienced technical specialists – for instance a geotechnical review board.

For the south wall pushback study, the initial focus was on achievement of the general design criteria as suggested in the Guidelines for Open Pit Slope Design (Table 1 above). Given the high levels of confidence in the site geological and hydrogeological models and the significant database of geotechnical properties (including those gained from back-analysis of previous slope failures and current secure slopes) the mine, with agreement by its Geotechnical Review Board (comprising a number of eminent mining and geotechnical practitioners), identified that a lower slope design acceptance criterion could be accepted. The identified design was subsequently subjected to qualitative risk assessment before being considered to be at a pre-feasibility level.

7 Design implementation and reconciliation

The development of design criteria and incorporation of these into a mine design and schedule/plan is only the first part of the mine development process. In all study reports, the design consultant will strongly state that the proposed designs will only be achieved if appropriate care is taken in order to minimise rock mass damage as a function of drill, blast and excavation practices. This is sound advice, but in a production environment, things can go wrong and costs of such careful practices can be challenged and ultimately modified. In these instances management of change processes should be undertaken to ensure that the changes are well understood by the production, technical and management stakeholders such the potential risks presented by the change can be understood and managed. Similarly, reconciliation of proposed design with actual achieved excavation geometry is critical in order to provide the greatest likelihood of achieving the identified project value. An example of this process is discussed in Seery and Lapwood (2007). In reconciling excavated walls to design one matter which can often be overlooked is the drainage or depressurisation state of the slope in question. Pore pressure, or drainage state, is always quoted as part of design. As such we need to ensure that the appropriate measures are implemented to achieve the assumed water pressures, or we are not achieving our design. These matters are considered even more important in large slopes than in those of lesser height.

8 Conclusion

Given the limited experience of open pit mine slopes being extended to depths greater than 500m, the industry is still learning on how best to design these slopes. The efforts being made under the direction of the LOP group are a move in the right direction. These need to be coupled with the same basic principles which we apply in all slope design, namely the need for a comprehensive knowledge of

- the structural geology of the ore body and surrounding country rock,
- the properties of the soils, rocks and discontinuities,
- the site hydrogeology and hydrology, and
- the stresses which will be imposed upon the excavation as a function of the proposed mining

Back-analysis of previous failures as well as current “stable” slopes should be undertaken to build confidence in estimates of rock mass strength.

The challenging of our models by use of external reviewers is a good way of identifying and assessing technical risk. This combined with analysis of the sensitivity of key components to your design outcomes will be critical in building confidence in your design process and the defined recommendations.

Time and effort needs to be spent up front on detailed analysis of the potential excavation design options before a single option is chosen for further study, and ultimate implementation. It is much easier to change tack at an
early stage before other downstream processes have come to depend on the outputs of a flawed option at a late study stage.

For all mine slopes displacement monitoring is essential for management of safety and production consequences of slope failures. It will not necessarily be of benefit in protecting the value of the project on which funding was initially approved. As a mine geometry changes, so does the value.

9 Acknowledgements

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10 References