COMPREHENSIVE BACK ANALYSIS TECHNIQUES FOR ASSESSING FACTORS AFFECTING OPEN STOPE PERFORMANCE

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A methodology and a number of software tools have been developed to assess the operational and geotechnical factors affecting the performance of open stoping operations. The paper describes the tools and techniques for collecting and analysing common factors affecting performance, such as drill and blast, development undercutting, stress induced damage, rock mass quality, and large scale geological features. Example data has been collected and analysed with some results presented.

Keywords: back analysis; open stoping; dilution; over-break.

1. Introduction

The Western Australian School of Mines (WASM) is currently conducting research into optimising the design and extraction sequence of open stoping excavations in highly stressed rock masses. A large component of this study will involve back analysis of stoping activities from a number of participating mines. In this regard, the project initially aims to identify and assess the contributing factors on large excavation performance. As part of this research, a number of techniques and software tools have been used to assist in the back analysis of stoping performance at a number of open stoping operations in Australia. This paper describes some of the techniques and tools utilised to undertake back analyses of open stope performance data.

Open stope performance is generally measured by the ability to achieve maximum extraction with minimal dilution. Hence, the success of the open stoping method relies on the stability of large (mainly un-reinforced) stope walls and crowns as well as the stability of any exposed fill masses (Villaescusa, 2004). The success or performance of an open stope can therefore be judged on the actual outcome versus the planned outcome, in terms of the final volume, tonnage and grade of material extracted, and the timeliness of extraction, compared to the planned design and schedule.

2. Over-break and Under-break

The two main physical criteria for assessing stope performance are the over-break volume, and the under-break volume. Over-break refers to the volume of material excavated in excess of the planned stope design volume (or “reference” volume), and under-break refers to the volume of intact rock material left unexcavated relative to the planned stope design volume.

2.1. Reference Volume

Over-break and under-break data are derived by comparing models of the final stope void volume to a “reference” volume. The “reference” volume usually consists of the stope design and in-place
development, however, this may need to be modified if any changes were implemented during excavation. For example, additional holes may have been drilled and fired that were not on the production plan or, conversely, drilled holes were not fired due to bridging/blockages or due to a decision to leave a pillar.

Common practice in the mining industry is to represent the planned fired stope geometry as a triangulated irregular network (TIN) wireframe volume, using solid modeling facilities in mine planning software.

2.2. Cavity Monitoring Surveys

To obtain a quantitative measure stope performance, final excavated volumes need to be obtained and compared to the stope design boundaries. Cavity Monitoring System (CMS) surveys have been a well established method for surveying inaccessible open cavities in underground mining operations for well over 10 years. The CMS was developed jointly by Noranda Technology Centre (NTC) and OPTECH Systems, Canada (Miller et al., 1992). This system is widely used in Australia's underground operations, especially in Western Australia (Jarosz and Shepherd, 2000).

The general process for developing a final stope void volume generally consists of; data acquisition utilising CMS survey techniques, data filtering of redundant points (including CMS outlier/spike identification and removal), CMS amalgamation (where required, involving merging/combining a number of CMS surveys taken from a variety of sites), and final void modelling of CMS data.

The final void volume generally consists of generating a TIN wireframe model in mine planning software, based on the CMS survey data. Common practice is to generate slices through the raw CMS data, filter the slices to reduce redundant points and re-generate the volume. Depending on the choice of slice interval and filtering level, this process can severely affect the precision and accuracy of final void model. In addition, the treatment of “blind-spots” or shadow areas, as well as presence of broken material or rill in the stope will significantly impact on the accuracy of the final void shape.

2.3. Calculation and reporting of Over-break and Under-break

Over-break and under-break volumes are generally calculated by intersecting the “reference” volume with the final stope void volume utilising mine planning software, typically using triangulation intersections of the relevant TIN wireframes. Depending on the relative configuration and aspect ratios of individual triangles within the wireframe models, errors may occur during triangulation intersection process (principally due to floating point precision), resulting in an unsolvable volume intersection.

Tonnage and grade values of dilution and ore loss can also be calculated utilising the “reference” and final stope void volumes in conjunction with a block model of reserve grades and densities, including backfill materials. These data can then be stored in a database for further reconciliation reporting and presentation (Morin, 2006).

3. Factors Affecting Stope Performance

Clark and Pakalnis (1997) briefly summarized some of the major factors affecting stope performance, such as: stope geometry, development location and undercutting, rock mass characteristics, in situ and induced stresses, large scale geological structures, rock reinforcement,
drill and blast processes and time dependency.

To assess the influence of each of these factors on stope performance, it is necessary to adequately characterise and/or quantify the factors both prior to and during excavation process. This requires all personnel involved in the design and production stages to record relevant information, such that it can be reviewed on completion of the excavation (Villaescusa, 1998).

Stope performance reviews act as a technical audit to the stope design process (Villaescusa, 2004). These findings can be used to develop improved design and engineering tools for optimising stope and pillar design, layout and sequencing, as well as implementation practices. In this regard, it may be necessary to develop a database of these major factors, in conjunction with the physicals obtained from CMS analyses.

4. Back Analysis Techniques

Interest has been shown in trying to understand the relative influence of each of the factors mentioned above for use in optimising the planning and design of open stopes. A variety of back analysis techniques have been explored. For example, Wiles (2006) uses back analysis results from linear elastic numerical modeling to indicate the reliability of stress-related damage and failure criteria, Suorineni et al (1999) investigated the influence of the location and orientation of fault structures on open stope over-break using 2D hybrid boundary-finite element studies, Stewart (2005) attempts to relate blast hole design, stress damage and relaxation to the amount of over-break in narrow vein stopes using statistics and empirical stability graph techniques, and Wang (2004) looks at the effect of undercutting on over-break. These approaches may be appropriate if the dominate mechanism can be identified, however, they may not be considered comprehensive as each factor is investigated separately, with the influence of other contributing factors not readily accounted for. A methodology, therefore, is required to account for and assess the relative influence of each individual factor on stope performance.

5. Proposed Methodologies

A methodology is proposed to assist in the confirming, or otherwise, of hypotheses intimating the relative contribution of various factors and their influence on open stope performance. This methodology can utilise, for example, the results of:

- candidate criteria developed from numerical modelling,
- over-break and under-break analysis,
- modelling of large scale geological structures,
- rock mass quality modelling,

The methodology relies on the ability to query the volume of rock around the excavation under analysis to select regions fitting various candidate criteria thought to contribute to over-break. The advantage of this system to other empirical approaches lies in the ability to test various candidate criteria simultaneously and also account for spatial variability of component parameters. Alternatively, the methodology can be used to test the null hypothesis of any developed criteria (i.e. to test regions of the rock where over-break is not anticipated).

5.1. Implicit Surfaces

The proposed methodology involves fitting implicit surfaces, defined by radial basis functions (Carr et al, 2001), to candidate criteria and other features of the rock mass. The use of
mathematical radial basis functions allow for relatively complex mathematical intersections and/or unions of these implicit surfaces or volumes. Implicit surfaces can be used in a variety of back analysis processes, for example, over-break and under-break analysis, where they are superior compared to the known issues associated with triangulation intersections (see Section 2.3). Example CMS data, taken from Kanowna Belle Gold Mine, was modelled using implicit surfaces. Figure 1 shows the highly detailed model, which honours all CMS data points, and is compared with a traditional filtered triangulation model. Implicit surface intersections offer advantages when generating additional over-break and under-break data, such as:

- Depth (i.e. perpendicular distance to reference volume) of over-break and under-break,
- Volume of over-break and under-break, and
- Area of over-break and under-break

Due to the highly detailed nature of the output, it can also assist in identifying localisation of over-break or under-break. This information can provide information on the morphology, extent and nature of over-break. For example, the morphology can indicate whether the over-break was localised and tetrahedral in shape, possibly indicating a small structurally controlled wedge-type failure, or arciform and protracted, possibly indicating stress-related failure and subsequent “arching” response.

![Figure 1](image_url)

**Figure 1.** Design stope volume (dark grey) and CMS (light grey) for a) triangulated final void volume and b) final void volume based on implicit surfaces

Implicit surfaces can be used to model, for example, large-scale geological structures and their control on rock mass quality and subsequent influence on the levels of overbreak. Figure 2a shows two fault structures modelled from geological data, highlighting the occurrence of major over-break on the stope wall with its intersection with “Fault B”. Figure 2b shows the distribution of rock mass quality, in this case fracture frequency interpolated from borehole data, on the over-break surface. Figure 2c shows how the intersection of the two fault surfaces locally controls an increase in fracture frequency (isosurface value of 12 fractures per metre) in the area highlighted by the circle shown in Fig. 2b.

### 5.2. Candidate Criteria

The results from numerical modeling can also be incorporated into the back analysis methodology. Candidate surfaces based on say, a maximum shear stress criteria and/or confinement-based criteria, can be displayed alongside other candidate criteria and over-break data.
Figure 2. Results of geological modelling of a) two faults b) contours of fracture frequency on over-break surface, and c) interaction of faults, rock mass quality and over-break.

Figure 3a shows the results of linear elastic numerical modelling represented as implicit isosurfaces, together with over-break. Figure 3b shows contours of low confinement on the over-break surface, whilst Fig. 3c shows maximum shear stress, plotted as both contours on the over-break surface and as an isosurface.

Figure 3. Results of numerical modelling showing a) minor principal stress isosurfaces b) contours of minor principal stress on over-break surface, and c) isosurface of maximum shear stress and contoured on over-break surface.

5.3. Volumetric Queries

The implicit surfaces can then be used to generate queries within the rock mass based on intersections and unions of volumes (similar to Boolean “AND” and “OR” operations, respectively). For example, based on the data presented above, it is possible to select a volume of the rock mass around the excavation based on stress-based criteria and/or rock mass quality and/or distance to a prospective geological structure. In this example, a query was constructed using the following criteria;

• Maximum shear stresses greater than 15MPa,
• Distance less than 10m from “Fault B”, and
• Fracture frequency greater than 7

The resulting volume is shown in Fig. 4 and provides a very good correlation between the query volume and the location of over-break experienced during mining. Although “Fault B” transects the entire stope, Fig. 4b also highlights that its presence alone is not an indication that
over-break will occur. Figure 4 shows that intersection and union functions of implicit surfaces can be used as a valuable tool in determining the relative influence of various candidate criteria on stope performance.

![Figure 4](image1.png)

Figure 4. Results of intersection of multiple candidate criteria for stope AP02 looking a) north west and b) south east.

5.4. Candidate Criteria Reliability

Using an approach described by Wiles (2006), understanding uncertainty in observational back analyses can assist in determining the reliability of any forward analyses. Wiles (2006) describes the procedure for determining the reliability of candidate stress-based strength criteria and its use in failure prediction. An example of this approach is shown in Fig. 5. This approach can also be incorporated into this methodology by generating implicit isosurfaces of various prediction criteria, at a number of values, which could be used to represent probabilities of failure.

![Figure 5](image2.png)

Figure 5. Example of stress-based back analysis to determine reliability of developed strength criteria (after Wiles, 2006)
5.5. Stope Performance Database

Data generated from the tools above can be linked to a purpose designed stope performance database, along with CMS derived physicals and qualitative stope performance information.

The database contains relevant fields for quantitative and qualitative information in the following areas; general stope details, design details, rock mass and boundary condition data, drilling and blast, CMS and performance, reinforcement, extraction and filling data.

The qualitative information, mainly derived from the results of stope performance reviews, provides an important role in confirmation or verification of the impact of the various factors indicated using the volumetric querying techniques described in preceding sections.

Even simple queries from the stope performance database can be of benefit to understanding the controls on performance. For example, simple analysis of data obtained from the volumetric techniques, shown in Fig. 6, indicates that majority of over-break occurring on stope wall surfaces does not affect the entire surface. Figure 6a, indicates that localisation is common and only a few, small stope surfaces are affected by overbreak across the entire surface. Figure 6b displays a plot of average depth of over-break (volume of over-break divided by area of over-break) versus stope wall surface area. This plot can highlight the propensity of potential structurally controlled failures, described by points with high average depth of failure compared to the surface area.

![Figure 6. a) Plot of area of over-break versus stope wall surface area and b) average depth of over-break versus stope wall surface area.](image)

6. Conclusions

An improved methodology to understand the relative influence of the various factors that influence open stope performance has been proposed. The method allows for the simultaneous investigation of various factors, such as rock mass parameters and the results of numerical modelling, the integration of the spatial variability of parameters, and ability to query the rock mass volume for a variety of candidate criteria. The methodology is not a replacement for traditional analytical or
numerical techniques, yet provides a framework for integrating and interrogating results from these techniques.

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References


