Dilution optimisation in sublevel open stoping operations

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INTRODUCTION

Dilution is associated with considerable direct and indirect costs in underground open stoping operations. As shown in previous works, an improved ability to predict dilution enables the economic risks associated with unplanned dilution to be reduced. Depending on the width of the orebody and depth of mining, the economic performance of an open stoping operation can become even more sensitive to dilution.

It is shown in several well-documented studies that as little as 1 per cent of additional dilution can impose millions of dollars of lost profits per annum. Optimisation of a stoping operation is therefore largely dependent on the ability of the operation to minimise dilution. This can only be achieved through sensible analysis of past and future performance of mined stopes using the most appropriate recent available technologies and tools.

This article presents a new design process that utilises advanced geotechnical numerical modelling and various other analytical tools to assist with a more robust mine design of open stoping operations. The focus of this design process is on geotechnical factors affecting dilution during the life-of-mine.

A recent application of this optimisation method for a mining operation is presented in this paper as a case study. Through the application of this method and various other operational improvements, the mine was able to deliver more consistent production and lower operating costs over its life-of-mine outlook and was able to reduce dilution by up to 50 per cent and achieve sustainable record high production rates.

Previous works on narrow vein orebodies completed by Stewart and Trueman (2008) shows the increasing economic effect of unplanned dilution for narrower ore widths (see Figure 1).

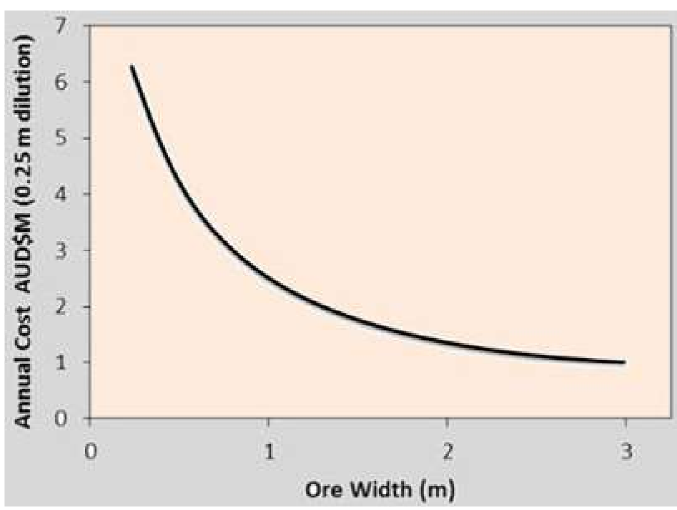

FIG 1 – Annual operating cost for 0.25 m of dilution for typical narrow vein mine (after Stewart and Trueman, 2008).

The relationship between dilution and direct operating cost at varying depths for a mining operation in Australia is also shown in Figure 2.

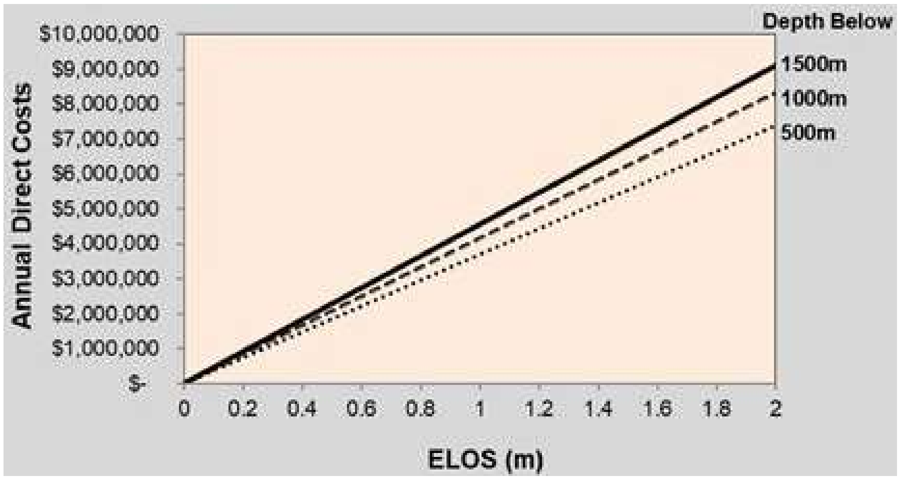

FIG 2 – Annual direct cost associated with dilution at various mining depths for a mining operation in Australia.

Despite the significant impact that dilution can have on the economic performance of underground operations, the standard practice for prediction of dilution is still based on outdated empirical and benchmarking techniques. These techniques have several limitations which are often ignored by many practitioners. As a result, many stoping operations have ongoing unresolvable dilution issues. In many instances, dilution issues are considered unpredictable or unmanageable, or they may be associated with localised rock defects that are not predictable.

Detailed geotechnical reconciliation and dilution optimisation are rarely completed. This translates to a missed opportunity for measurable improvements to overall mine economics.

The approach that is developed by the authors follows a structured process that can significantly improve the reliability of dilution prediction and can assist in finding optimum strategies to minimise dilution. This approach makes use of the most recent computing hardware and software advances in geotechnical engineering and computer simulations to replicate the geotechnical mechanisms that cause dilution.

The steps required for this approach are not complicated, and typically include:

- Stope performance assessment and analysis of historical excavated stopes.
- Analysis of factors affecting stope stability, considering mine-specific factors, and developing predictive methods and models to forecast the future performance of planned stopes.
- Calibration, or validation of actual-versus-predicted stope performances through back analysis.
- Forecast of future stope performances to fine-tune the mine design parameters and assist with planning.

STOPE PERFORMANCE ASSESSMENT

Stope performance is often assessed through the ability to obtain maximum ore recovery with minimum dilution. Cavity surveying systems (such as CMS and C-ALS) are critical in allowing detailed reconciliation and comparison with the original stope design and measuring stope overbreak or underbreak for individual stope walls. This allows accurate estimation of dilution and ore loss to be completed, building on work being performed by survey and geology teams.

For 'geotechnical' reconciliation assessments, however, this task is usually conducted manually. It is labour-intensive and time-consuming and is therefore limited to a few sampled stopes. As a result, there is usually an insufficient number of stopes being reconciled to enable a representative statistical analysis to be performed.

Authors make use of fully-automated computer programs and macros that can complete stope performance assessment from cavity survey data significantly faster and more accurately than other available techniques.

As shown in Figure 3, this technique uses a 3D meshing routine (similar to a block model) to fill the cavity survey and design wireframes, then overlay the two meshes on each other. A computer engine then calculates the differences between the two meshes to output the overbreak and underbreak values for each stope wall. The block models, geological wireframes, and orebody wireframes can also be incorporated into these calculations.

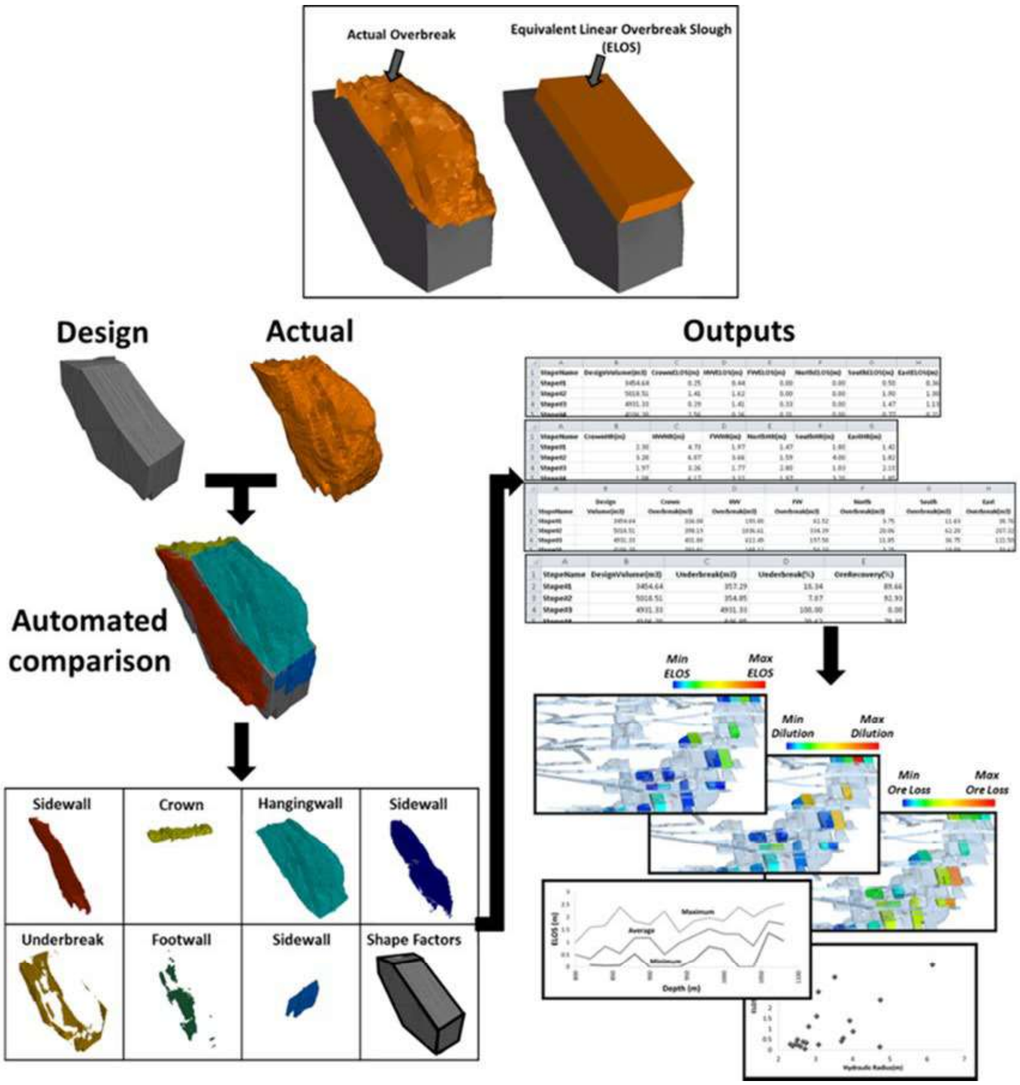

FIG 3 – Automated stope reconciliation assessment.

The outputs from this engine are equivalent linear overbreak slough (or ELOS as introduced by Clark and Pakalnis, 1997), overbreak or underbreak volumes, overbreak or underbreak percentages, and breakdown of material types (such as rock type, ore/waste, and fill) for all assessed stopes, with a breakdown of values for each stope wall.

This refines and enhances work being done for Mine to Mill reconciliation to identify geotechnical characteristics responsible for dilution. This method can complete the performance assessment for hundreds of mined stopes in a short period, generating a complete geotechnical reconciliation database.

ANALYSIS OF FACTORS AFFECTING STOPE STABILITY

Geotechnical factors are amongst the most important parameters affecting dilution. They include rock mass quality, mining sequence, induced stresses, mining depth, stope dimensions, stope geometry, orebody geometry, and proximity to major geological structures. These factors are very site-specific and vary largely from one mine to another. Therefore, for any predictive model or system to be effective, it needs to account for these factors on a site-by-site basis.

Therefore, for site-specific variables to be well understood, empirical and benchmarking systems may not provide reliable insight into the likely mechanisms affecting a particular operation. These empirical systems can only be used when all the limitations for specific mine sites are fully appreciated, and the possible sources of error are adequately quantified and accounted.

BACK ANALYSIS

For computer analysis, the proposed method makes use of state-of-the-art technologies in computational geomechanics and computer simulations to develop predictive models for different mining scenarios. In the proposed framework, FLAC3D (Itasca Consulting Group Inc., 2012) solver is used together with StopeX (Cavroc Pty Ltd, 2017). StopeX is a plug-in to FLAC3D which significantly simplifies the application of advanced numerical modelling and brings a much more advanced material model called Improved Unified Constitutive Model (IUCM). This makes it possible for all geotechnical practitioners, and not just specialist consultants, to learn and apply a more rigorous analysis than the current empirical and numerical tools.

Sufficient and high-quality geotechnical data is the critical input to these models to ensure reliable predictions. However, for any predictive model, back-analysis and calibration are necessary to ensure that models are validated against known past performance.

For back-analysis, the geotechnical stope reconciliation database is often the primary source that is used for comparison with the model outputs. However, often, other data such as development damage mapping, monitoring data and high-quality seismic databases are also used to compare the actual versus model performance.

FORECASTING FUTURE STOPE PERFORMANCE

The validated predictive dilution models are valuable tools for mine-design and to assist with short to long-term mine planning. These models provide vital input to mine planners and geotechnical engineers to:

- foresee operational bottlenecks resulting from unplanned stope dilution
- identify optimised strategies to minimise dilution
- optimise stope dimensions and geometries
- optimise stoping sequence
- compare and analyse various mining scenarios to identify trade-offs between production rates and expected dilution.

CASE STUDY

A recent application of this dilution optimisation method for a mine in Australia showed a great success.

Despite the fact that the mine is located in a challenging geotechnical environment, it was able to deliver more consistent production and lower operating costs over its life-of-mine outlook. Through systematic dilution optimisation methods, the mine was able to reduce dilution by up to 50 per cent and achieve sustainable record high production rates.

In the first and second year, before this method being implemented, the mine experienced increased stope hanging wall dilution. Individual stopes experienced ELOS exceeding 7 m (up to 40 per cent dilution). The total annual dilution reached 11 per cent in year 1 and 16 per cent in year 2.

Together with the site personnel a series of studies were completed over three years to address the dilution issue. The key milestones for this project were to:

- Identify the main contributing factors affecting the stope hanging wall dilution.

- Develop a predictive model to assist the mine in foreseeing the expected dilution resulting from planned stoping sequences.
- Evaluate the future long-term mining scenarios and assist with finding the optimum mining strategies that can maximise production and minimise the stope hanging wall dilution.

HISTORICAL STOPE PERFORMANCE ASSESSMENT AND IDENTIFYING KEY FACTORS AFFECTING DILUTION

The first step, to find the main controlling factors, involved a detailed analysis of historical stope performances. For this purpose, various information was analysed, including stope design and as-built shapes, stope-strike-length, mining sequence, rock mass quality and backfill sequence. Examples of these analyses are shown in Figure 4.

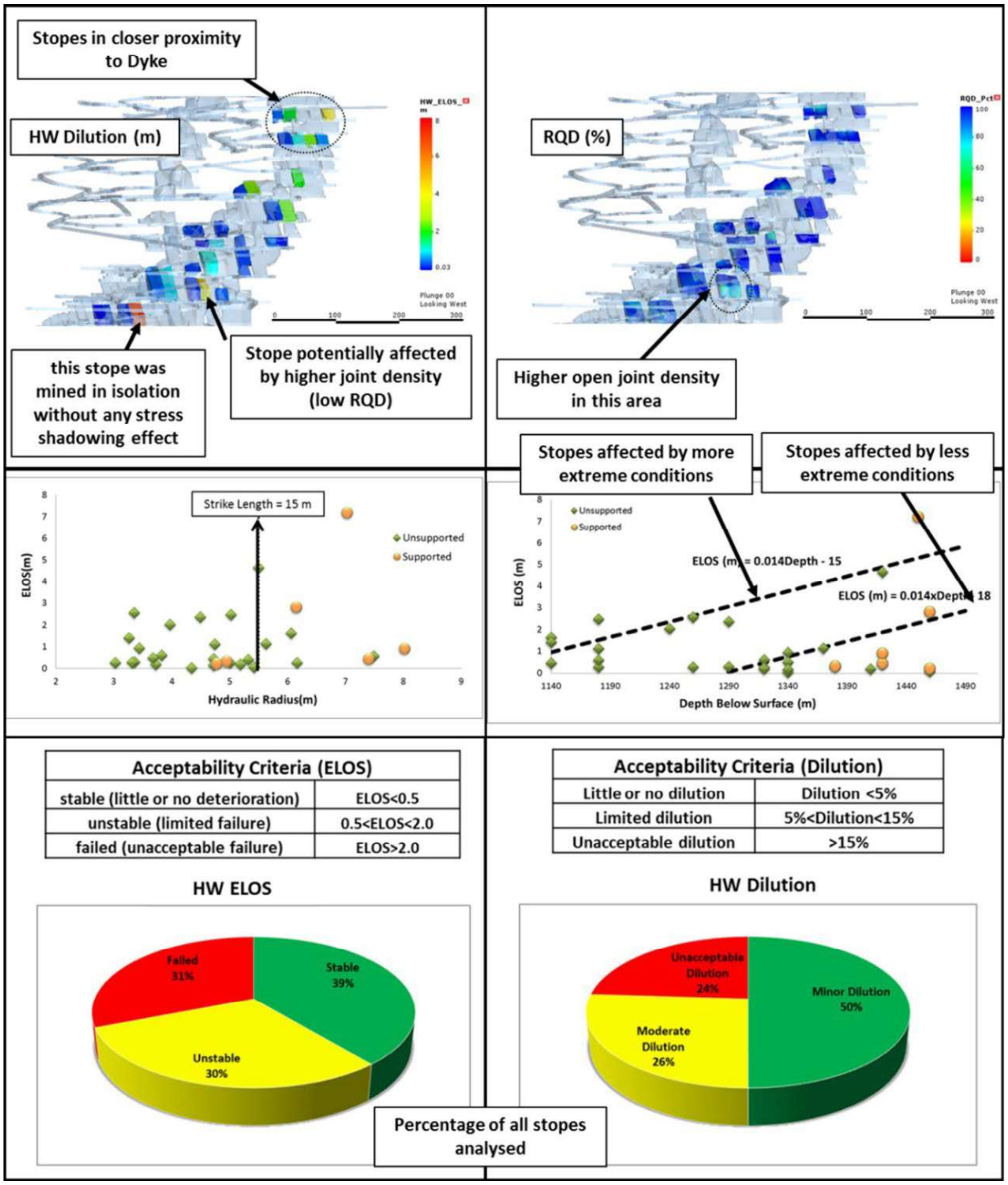

FIG 4 – Historical stope performance assessment (for year 1 and year 2).

The historical stope performance analyses identified some key factors and conclusions relating to the hanging wall dilution, including:

- The first stope on each level had increased dilution while subsequent stopes showed considerably lower dilution. Stress shadowing effect was found to be the leading cause.

- South to north stope retreat showed more dilution than north to south retreat. This was mainly associated with pre-mining stress orientation and geotechnical characteristics of the hanging wall.
- Stopes with a strike-length shorter than 15 m showed considerably lower dilution.

DEVELOPMENT OF A PREDICTIVE DILUTION MODEL

Once a good understanding of the previous stoping performance was attained, predictive models were constructed and validated against the past performance data. Figure 5 shows some of the outputs from the back analysis study and the correlation with the actual stope performance.

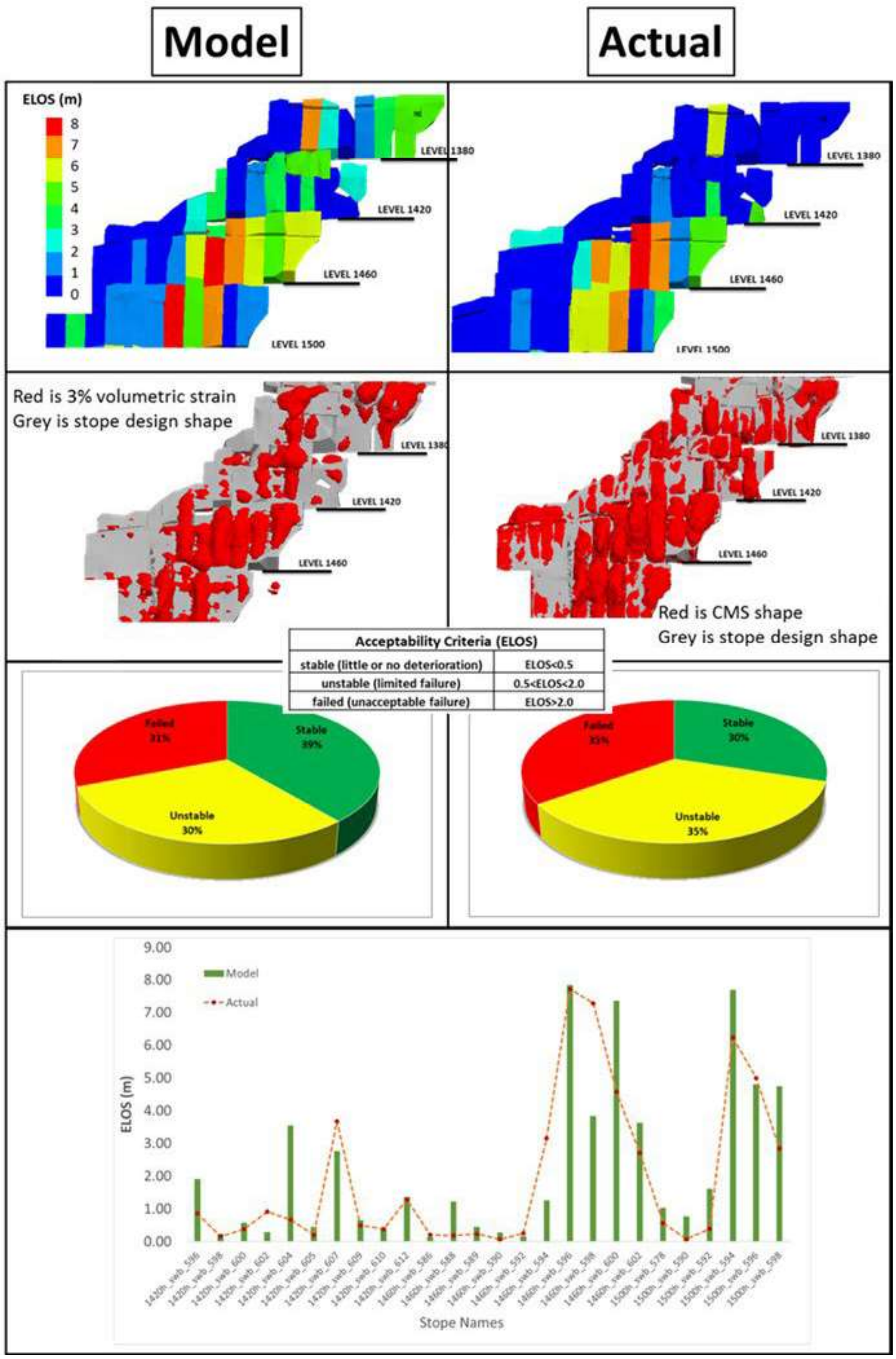

FIG 5 – Validation of the predictive model through back analysis of historical stope performance.

The modelling method plays an important role when dealing with dilution assessment in high stress or more complex rock mass conditions. At the subject mine site, the predictive numerical models prepared previously were not able to capture the observed hanging wall failure mechanism accurately. This was found to be largely due to the limitations of the applied modelling method.

In this framework, Mining One uses the IUCM (Vakili, 2016) modelling method that can account for complex geomechanical failure mechanisms causing hanging wall dilution. This method was able to capture many of the observed mechanisms leading to increased dilution at the subject mine.

The model was validated against the historical dilution data but also several other geotechnical performance indicators such as drive damage mapping, hanging wall SMART – cable monitoring and the seismic data.

STOPE SIZE OPTIMISATION

Following the initial investigation and review of historical stope performance, the validated dilution model was used to find the optimised stope layouts to minimise and control dilution. The following questions were raised to be answered through further analysis:

- What is the optimised stope strike length to manage unplanned dilution without any compromise on production rates?
- Considering the observed stress shadowing effect, is it necessary to have reduced stope strike length for all the planned stopes? Alternatively, is it possible to reduce the strike length only for the first stope on each level?
- Is it possible to optimise the excavation geometry of the hanging walls to manage the expected failure mechanism better?

To answer these questions, Authors, together with the site personnel, constructed and analysed several models and scenarios. These different scenarios were compared quantitatively, as shown in Figure 6, and the following conclusions were obtained:

- Reducing the strike length of only the first stope showed a significant reduction in dilution without any significant compromise on production rates.
- It was shown in the models that reduction of the strike length for the first stope on each level had a minimum impact on stress-shadowing effect and its benefits. Subsequent stopes on the level still showed considerably smaller overbreak than the first stope.
- Model results suggested that a de-stressing slot in the hanging wall of the first stopes can be very useful in minimising dilution, as it can create the same stress shadowing effect.

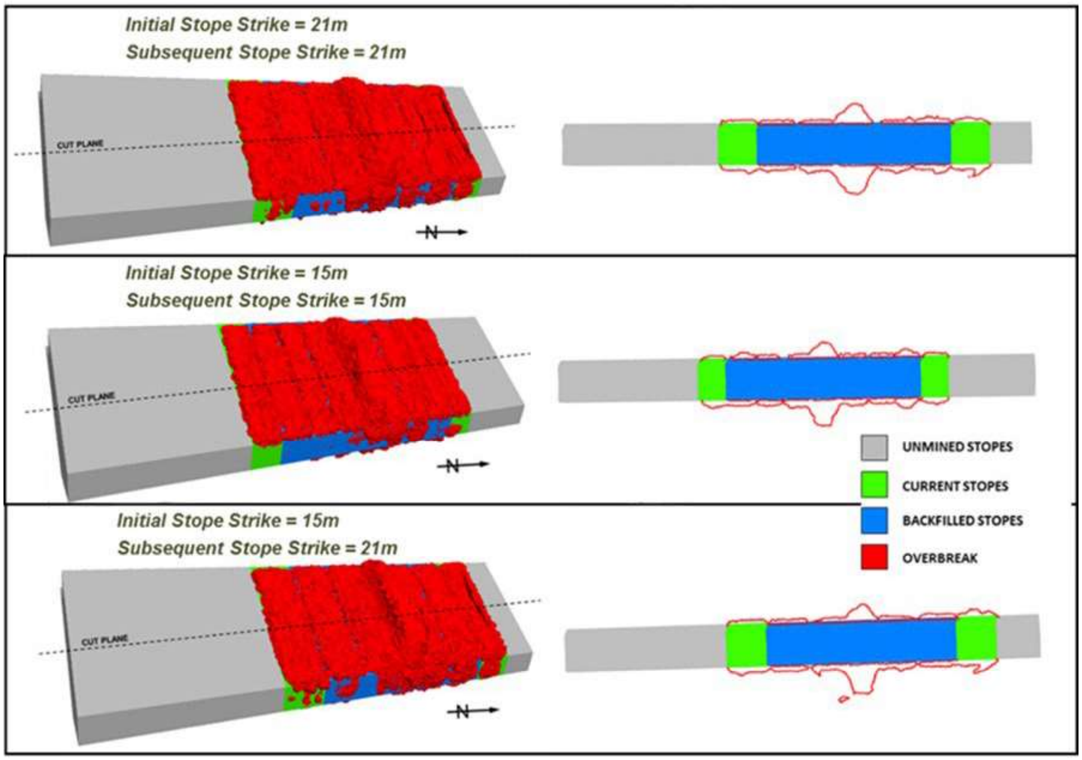

FIG 6 – Stope size optimisation analysis.

SEQUENCE OPTIMISATION

Historical mining identified two sequence-related factors that were considered to affect hanging wall dilution. First, south to north retreat, which is necessary when a centre-out chevron sequence is adopted. Secondly, due to the southerly plunge of the orebody and in order to maintain a centre-out down dip chevron sequence, the retreating front needed to be offset every two to three levels. The chevron offset was previously trialled which resulted in some adverse geotechnical conditions including hanging wall overbreak for stopes mined on the northern front.

From a purely geotechnical perspective, a north-to-south single end-retreat sequence was previously considered to be the most effective sequence to control hanging wall dilution. However, the single end-retreat has some shortcomings from a mine planning point of view, including less flexibility and fewer production rates.

As a result, it was decided to carry out a series of analysis to see if the chevron offset retreat sequence can be engineered or optimised. The aim was to consider a range of lead-lag options for the start of the offset, as well as different sequences regarding the formation of the closure pillar, extraction of the crossover stopes and subsequent mining of the remainder of the chevrons. Analysed options and comparisons with an end-retreat sequence are shown in Figure 7.

The following conclusions were made:

- The model with an offset distance of 42 m showed the lowest total dilution.
- Opening stopes on the offset level generated excessive dilution.
- An optimised chevron offset sequence can generate comparable results to a single end-retreat sequence.

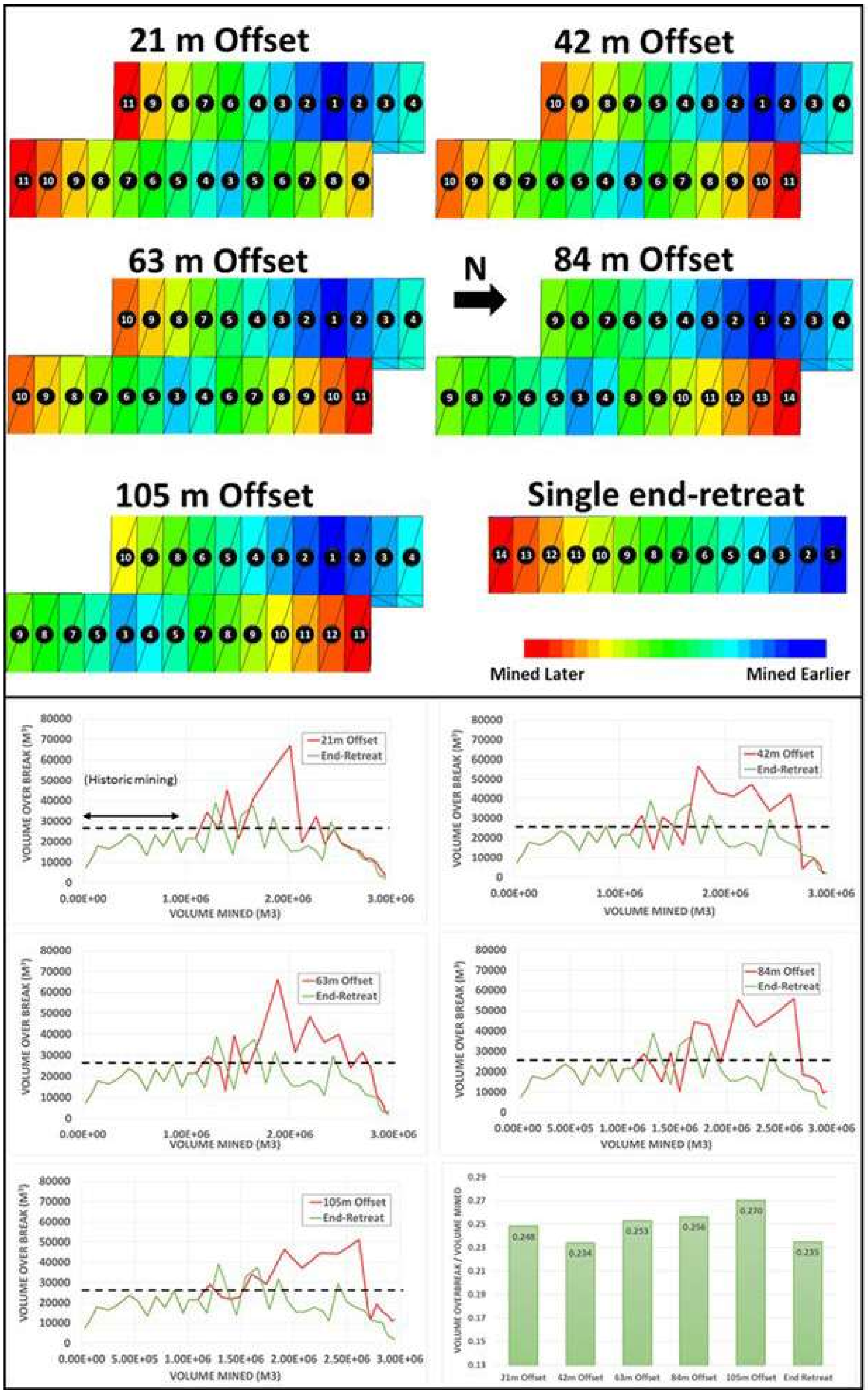

FIG 7 – Sequence optimisation analysis.

OPTIMISED MINING SCENARIO

As a result of sequence and stope size optimisation analyses, the mine site's planning team implemented some mine design measures to manage dilution better but also maintaining a sustainable production rate. These measures were included in an optimised mining scenario which included:

- a reduced strike length of the opening stope on each level from 21 m to 9 m
- a de-stressing slot in the hanging wall of the opening stopes
- a reduced strike length for the northern stopes (north of the opening stope) from 21 m to 15 m

- a chevron offset sequence, for maximum production potential from dual fronts on each level, using an offset distance of 33 m.

This optimised strategy was also analysed, using the calibrated numerical model, and it was compared against the original mine plan (end-retreat sequence). As shown in Figure 8, not only the optimised design resulted in a lower dilution than the end-retreat option, but it even showed reduced dilution compared to historical mining.

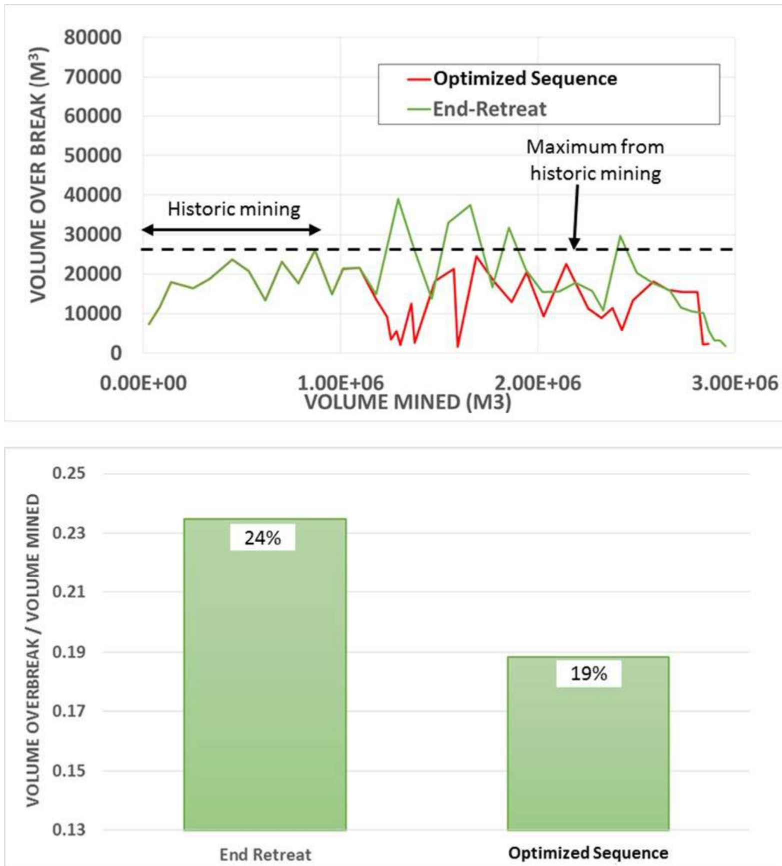

FIG 8 – Optimised mine design.

PROJECT OUTCOMES

The optimised mining scenario has been implemented at the mine site from year three on and results have been auspicious. Considerable reduction in dilution has been achieved, which was in line with model predictions. Summary of the critical improvements achieved are listed below:

- Overall annual dilution was reduced from 16 per cent in year two to 6 per cent in year three and 5 per cent in year four.
- Production was increased from 214 oz in year two to 267 oz in year three and 265 oz in year five.
- Cash operating costs were reduced from 690 (A$/oz) in year two to 609 (A$/oz) in year three and 592 (A$/oz) in year four.

Figure 9 shows the stope hanging wall conditions at the end of year four when the first offset level was successfully formed without any notable geotechnical problems.

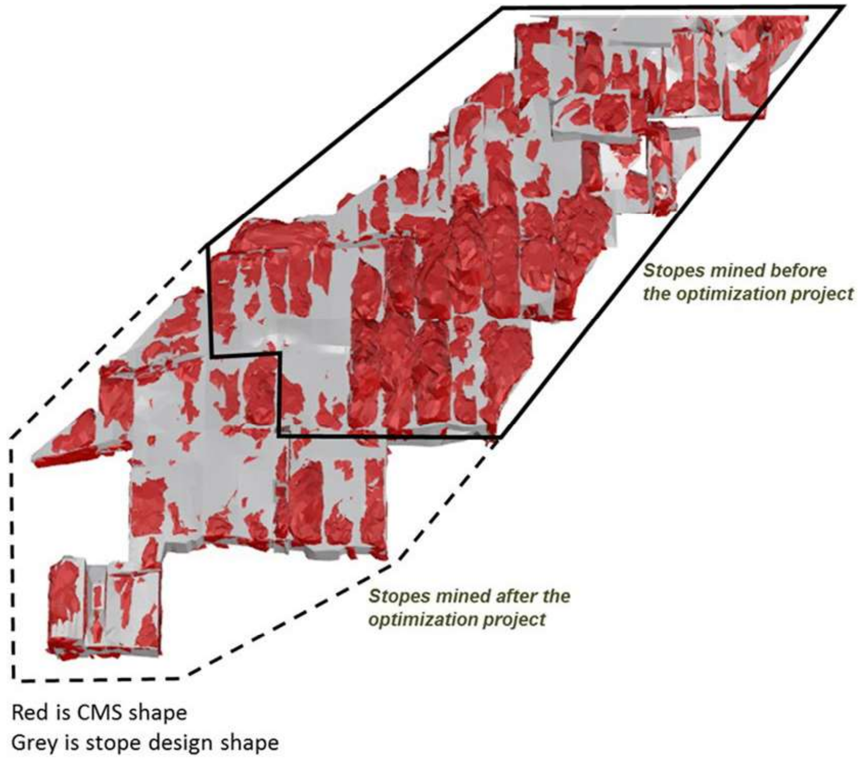

FIG 9 – Stope hanging wall performance at the end of year four.

CONCLUSIONS

Dilution is a significant source of direct and indirect costs in open stoping operations. The ability to predict dilution quantitatively enables the economic risks associated with unplanned dilution to be managed much more effectively. Depending on the width of the orebody and the depth of mining, the economic performance of operations can become even more sensitive to dilution.

The empirical, statistical and benchmarking methods or the outdated analytical tools are way too simplistic to enable effective prediction of future stope performance. These conventional methods, at best, are suitable for understanding the factors controlling the historical dilution and have several shortcomings when used for forecasting future dilution.

This paper presented a proven method that makes use of advances in computational geomechanics in a more practical way. Mining One believes that application of this approach in other open stoping mines can bring about significant economic and safety benefits. However, this requires a fundamental shift in management culture and avoiding over-reliance on outdated design methods.

Mines are developing into deeper and more challenging geotechnical environments. It is impossible to expect that benchmarking and empirical methods, which were originally derived from case histories in considerably different geotechnical conditions, to be able to guide us for future mine design.

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