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Integrating a new approach at the Westwood mine site for predicting the stope mined geometry

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Abstract

Open stoping has become a popular mining method in hard rock mines, not only due to the safety of the method as a non-entry approach, but also because of the high extraction rate and low costs. At mine sites, stope performance is evaluated by calculating stope overbreak using the Stability Chart. The limitations of the Stability Chart regarding the precision of the predictions, non-consideration of factors such as the influence of blasting, and the exclusion of underbreak have led to suboptimal designs. The modern capabilities of computers have resulted in large amounts of data being collected and despite subsequent statistical models being more capable, they have been underutilised in the stope design process.

To increase the information and knowledge that is extracted from the data and to progress from the simple qualitative per stope face prediction that is provided by a traditional Stability Chart approach, the Australian Centre for Geomechanics has developed a design approach that can account for many of the variables that influence stope performance and uses multivariate modelling methods to forecast the expected stope geometry. This approach is implemented as a stope reconciliation and design application and is integrated in mXrap software that allow users to import their stope design as well as their blasting design and predict the expected mined geometry for stope planification and optimisation.

This paper presents a case study of how the stope reconciliation and design application has been integrated at Westwood mine to understand and predict stope performance. An overview of the approach, the analysis of past stope performance and the generation of future predictions is presented along with the utility of this approach for optimising stope performance.

Keywords: *open stope, octree, machine learning, performance optimisation, dilution, overbreak, underbreak*

1 Introduction

Open stope extraction in underground mines is a popular approach to ore extraction due to this method's safety and economic benefits. Stope performance is typically expressed in terms of waste material inadvertently mined which is referred to as overbreak (OB) and ore which wasn't extracted which is referred to as underbreak (UB). Figure 1 illustrates the concept of OB and UB with respect to an open stope (Potvin et al. 2016). The volume of OB and UB is quantified by reconciling the stope design geometry and the mined geometry. The mined geometry is obtained by scanning the void using methods such as cavity monitoring systems (CMS) or drone mounted LiDAR. One of the main goals of a geotechnical stope reconciliation is to understand the root causes of OB and UB which in turn would improve design of future stopes.

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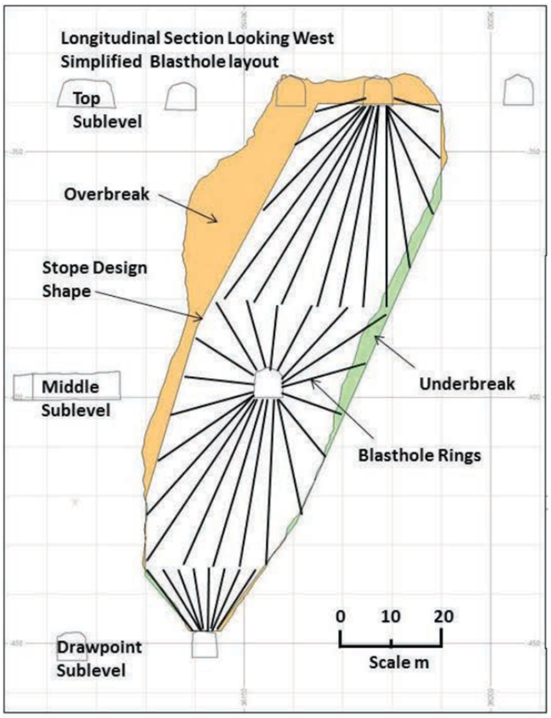


Figure 1 An example of stope overbreak and underbreak (Potvin et al. 2016)

The design of open stopes has seen little fundamental change over the previous decades since the introduction of the Stability Chart by Mathews et al. (1981). When forecasting the performance of stopes during the design phase, many operational mines are still heavily reliant on utilising this chart or its modified derivatives (notably Potvin 1988 and Nickson 1992). Some of the shortcomings include limited insight into the root causes of performance issues, a narrow scope of parameters considered, and a lack of consideration for UB. These parameters range from the geometry of the design and the geomechanical properties of the rock mass to major geological structures such as faults and shear zones, as well as operational variables like drilling and blasting techniques.

Significant technological advancements since the 1990s have enabled mine sites to gather a wealth of data with modern computers facilitating the management of vast databases comprising numerous parameters. This progression of hardware and software enables the development of new reconciliation tools working at a finer resolution. This allows for mines to evaluate stope design with sufficient resolution that captures spatial variation parameters that characterise geomechanical, geometrical, geological, and operational aspects along with the subsequent stope performance. These improvements facilitate a large leap forward for stope design tools for predicting and optimising stope performance.

The increased computational power has also enabled the ability to routinely run multivariate predictive models that are traditionally computationally intensive. This offers additional prediction approaches that were previously not available to mine site users that can consider a wide range of parameters. Despite these recent breakthroughs, the predictive tools often lack integration with contemporary mining practices and underutilise available data. This limitation hampers the optimisation of both stope design and performance prediction. However, recent work by McFadyen et al. (2023) proposed a new approach that integrates the breakthroughs (data at a fine resolution and multivariate models) when predicting the stope performance.

1.1 Objective

The objective of this work is to understand the root causes and expected magnitude of OB and UB at Westwood by considering parameters both existing and not a part of the existing approaches. Specifically, this approach aims to address deficiencies of the Stability Chart that can significantly influence OB and UB, namely drill and blast, major geological structures, and undercutting stope face. In addition to the knowledge acquired from this analysis, this paper also demonstrates how the new prediction approach is integrated in Westwood's stope design process to predict the expected stope mined geometry and optimise stope performance. This process is illustrated in Figure 2.

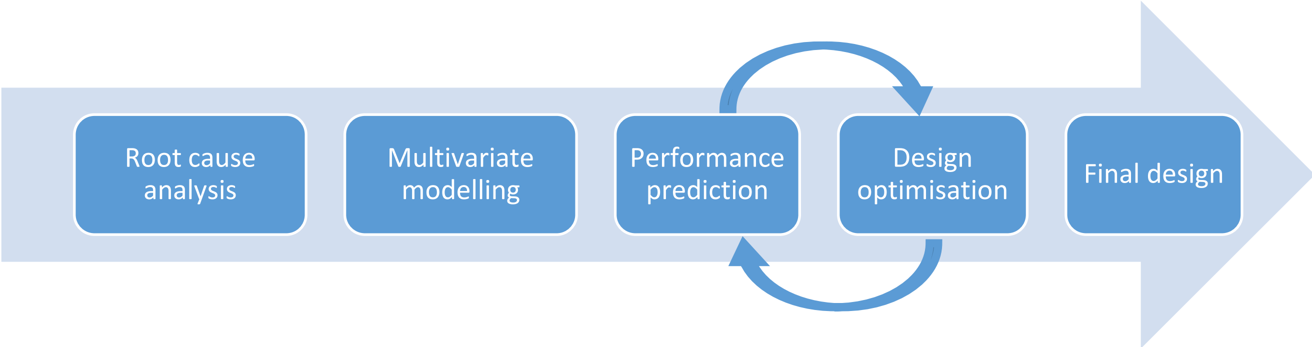


Figure 2 Conceptual overview of stope design process presented in this paper

2 Literature overview

Stope reconciliation can be considered at three different progressively finer levels of resolution. The level of resolution considered determines how performance is expressed and limits what root causes can be attributed to OB and UB.

2.1 Per stope

Common industry practice is to quantify the OB and UB for a whole stope (Potvin et al. 2020). The common metrics are the volumes of OB and UB as a percentage of the designed volume. Only global parameters can be quantified at this resolution and commonly include the mining method (e.g. primary–secondary stoping), the design volume, the mining sequence including if the stope was mined against backfill, the number of production blasts and the stand-up time.

2.2 Per face

Stope OB and UB are quantified on a per face basis routinely throughout the industry (Potvin et al. 2020). Often this is with a focus of problematic faces, e.g. hanging wall faces which often contribute a large amount of the overall OB.

Detailed analysis will resolve reconciliation for individual stope faces into groups that are characterised by similar mining conditions with an aim to identify these critical faces and quantify parameters that are the root cause of UB or OB. Common metrics for quantifying face OB and UB are simply these volumes of OB or equivalent linear overbreak slough (ELOS, Figure 3) introduced by (Clark 1998) and, for the UB, the equivalent linear lost ore (ELLO). The ELOS and ELLO are obtained by dividing the OB and UB volumes by the area of a face. These measures represent the average depth of the OB and UB for an individual stope face. It is typical to differentiate faces mined against backfill for the OB (Potvin et al. 2016). Analysis of individual faces allow for the quantification of various geomechanical, operational and geometrical parameters for root cause analysis however are often limited to factors integral to the Stability Chart.

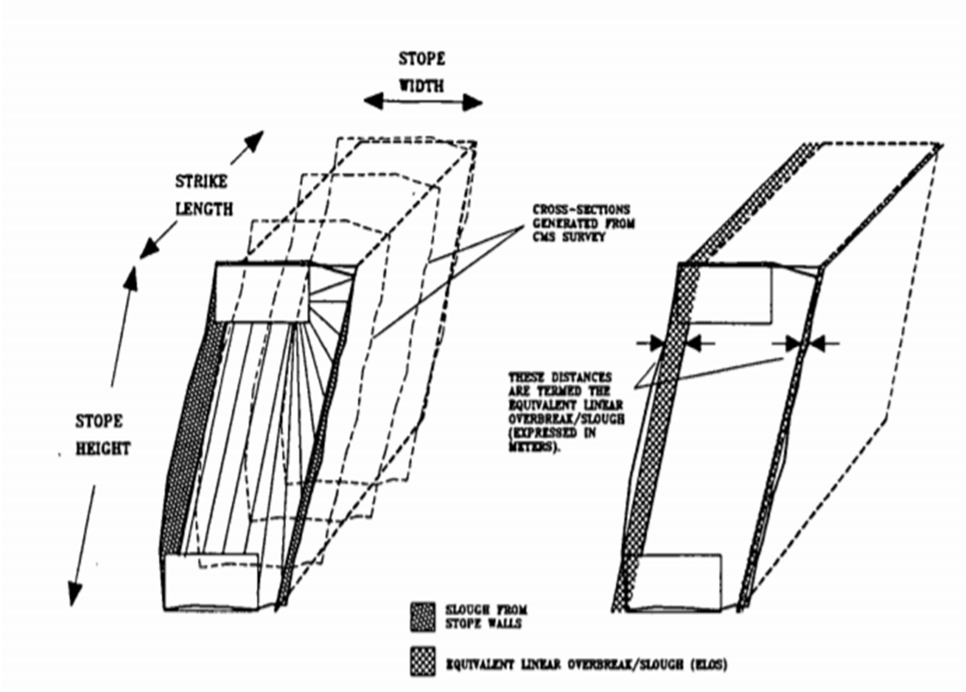


Figure 3 An illustration of equivalent linear overbreak slough (Clark 1998)

2.3 Per octree

Analysis of stope performance on a per octree basis allows for the stope to be assessed at a resolution where the variation of performance and influencing factors can be captured.

This analysis involves generating an octree data structure which partitions three-dimensional space by recursively subdividing octrees into eight octants. This subdivision occurs for octrees that are intersected by a surface until a desired resolution is reached. The minimum resolution is limited by computational constraints and is typically 1 m for large sublevel stopes and 0.5 m for smaller narrow vein stopes.

The octree data structure allows for parameters to be georeferenced to these points along the design surface as well as forming the basis for measuring performance. The performance for an octree representing an area on the design surface is quantified by calculating the distance between the design and mined surface along the design surfaces normal direction (Figure 4). This measure of performance is referred to as the projected distance and expresses OB as positive and UB as negative values.

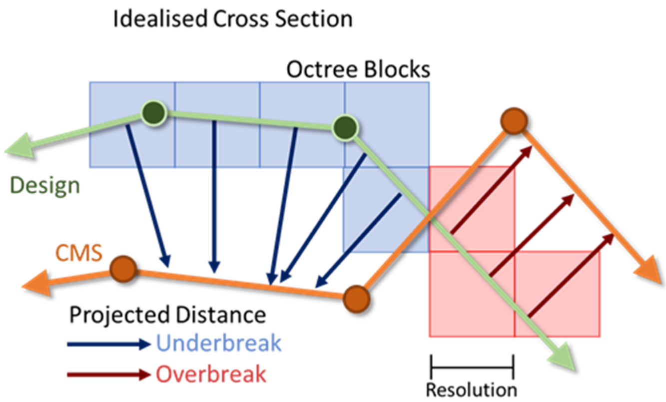
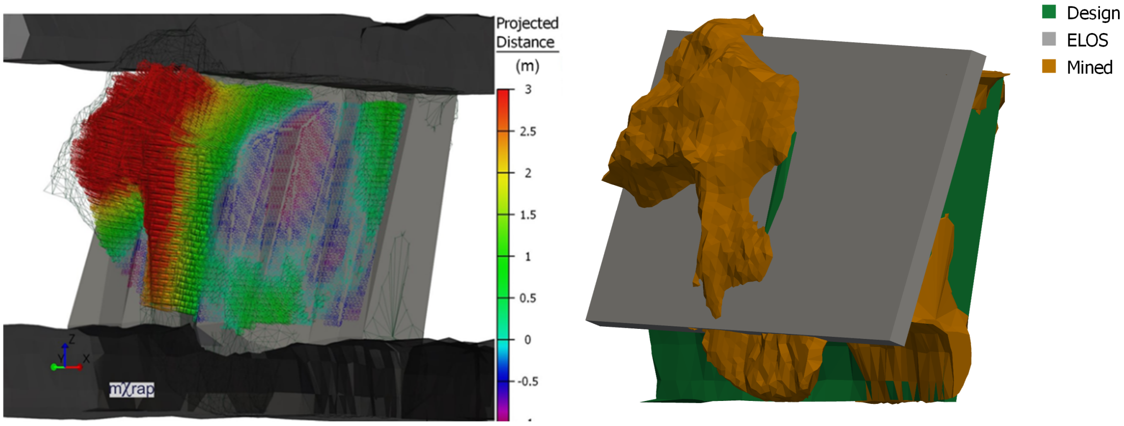


Figure 4 A conceptual illustration of projected distance derivation for each octree with respect to design and cavity monitoring system (CMS) surfaces (McFadyen et al. 2023)

This approach to stope reconciliation addresses the shortcomings of per stope and per face analysis by allowing for localised quantification of performance and the selected parameters. Figure 5 illustrates the dramatic variation of performance across a stope's hanging wall face (Figure 5a) (McFadyen et al. 2023) and the equivalent ELOS for this volume of OB (Figure 5b). It is evident that a per face style assessment cannot capture the variation in conditions or performance for this face. Ultimately, this impedes root cause analysis and the ability for sites to mitigate the conditions that contribute to poor performance for future mining. In contrast, this variation is comprehensively captured using an octree data structure with projected distances to quantify performance.



(a) (b)

Figure 5 (a) Performance variation for a stope's hanging wall face (McFadyen et al. 2023); (b) The equivalent linear overbreak slough (ELOS) for this volume of overbreak

3 Methodology

The proposed methodology aims to collect mine site data and generate information through quantification of parameters. Univariate, bivariate and multivariate statistical tools are used for root cause analysis to create the knowledge required for the prediction of stope performance and is integrated during the final steps of stope design This methodology has four key steps that enable the integration of predicted performance into the mining cycle:

1. data collection and parameter quantification
2. root cause analysis
3. predicting stope geometry
4. assessment of the predicted stope performance.

3.1 Methodology overview

Data collected related to the stopes (design geometry, CMS, drill rings) as well as the mining and geological environment (structural and geotechnical model, geometry of the drives intersecting the stopes). This data is then used to quantify parameters at an octree resolution that can influence stope performance. The following parameters were identified with associated category:

- Operational (drill and blast, undercut).
- Geometrical (design size and geometry).
- Geological (faults).
- Geomechanical (rock quality designation [RQD]).

The parameters are then used to understand stope OB and UB through root cause analysis. Univariate, bivariate and multivariate statistical tools are used to analyse the variance in the data and identify trends between the parameters and OB and UB to determine the critical parameters influencing the stopes' OB and UB. Multivariate analysis techniques, specifically, principal component analysis and partial least squares (Pearson 1901) inform on the correlation and independencies between the parameters. PCA and PLS models are generated using the free software environment R (R Core Team 2021).

A machine learning model utilises the critical parameters identified from root cause analysis to predict the spatial distribution and magnitude of the OB and UB on the octree data structure associated with the design surface. A random forest model is used due its ability to capture complex multivariate data structures and the probabilistic approach that can be developed. This model was also generated using the free software environment R (R Core Team 2021) along with the Ranger package (Wright & Ziegler 2017)

Random forest modelling results in a predicted projected distances with a standard error for an area of the design surfaces, giving a prediction interval. Further utility of these results is realised by generating volumetric information for different percentile of the interval. These predictions are sufficiently dense to form an oriented point cloud for a predicted mined volume. A predicted mesh is constructed using Poisson surface reconstruction in the free software CloudCompare (Girardeau-Montaut 2022) and its PoissonRecon plugin (Kazhdan et al. 2006). This mesh provides a predicted surface that can be reconciled with the design surface and results in predicted OB and UB volumes.

The various steps in this methodology are all completed in the mXrap software. Stope reconciliation in mXrap is continually being developed to add capabilities and to streamline workflows. Currently, this software environment takes the form of two main apps. The first app, the stope reconciliation wizard, is broken into specific processes for the quantification of design parameters, blasting parameters, reconciliation, and performance predictions. For the latter, the required R and Cloud Compare software is integrated to be run from the mXrap environment. The second app focuses on statistical analysis of observed and predicted stope performance. This analysis allows for the filtering of data based on various attributes and comprises of areas for per stope, per face and per octree focused assessments along with the comparison of predicted to observed stope performance.

4 Case study

4.1 Westwood mine site

Westwood mine is located in Abitibi-Témiscamingue, Québec, Canada, and comprises of three types of mineralisation (North Corridor, Zone 2 Extension, and Westwood). The Z2 Extension is interpreted as originating from the emplacement and crystallisation of late phases of the Mooshla pluton (i.e. intrusion-related gold). The North Corridor and Westwood are part of a gold-rich hydrothermal system (Yergeau et al. 2015). The Westwood sector is relatively complex, with numerous lenses embedded in different geological units, varying hydrothermal alterations in intensity depending on distance from the source, a metamorphic gradient change from green schist to lower amphibolite at depth, and a complex structural context with four joint families (Figure 6). Longitudinal stoping is used to extract the ore and is very thin due to the geometry of the mineralised lenses. Typical dimensions for a stope are a thickness (footwall-hanging wall span) of 2.8 m, a width (strike length) of 17 m, and an average height of between 25–30 m (Figure 7).

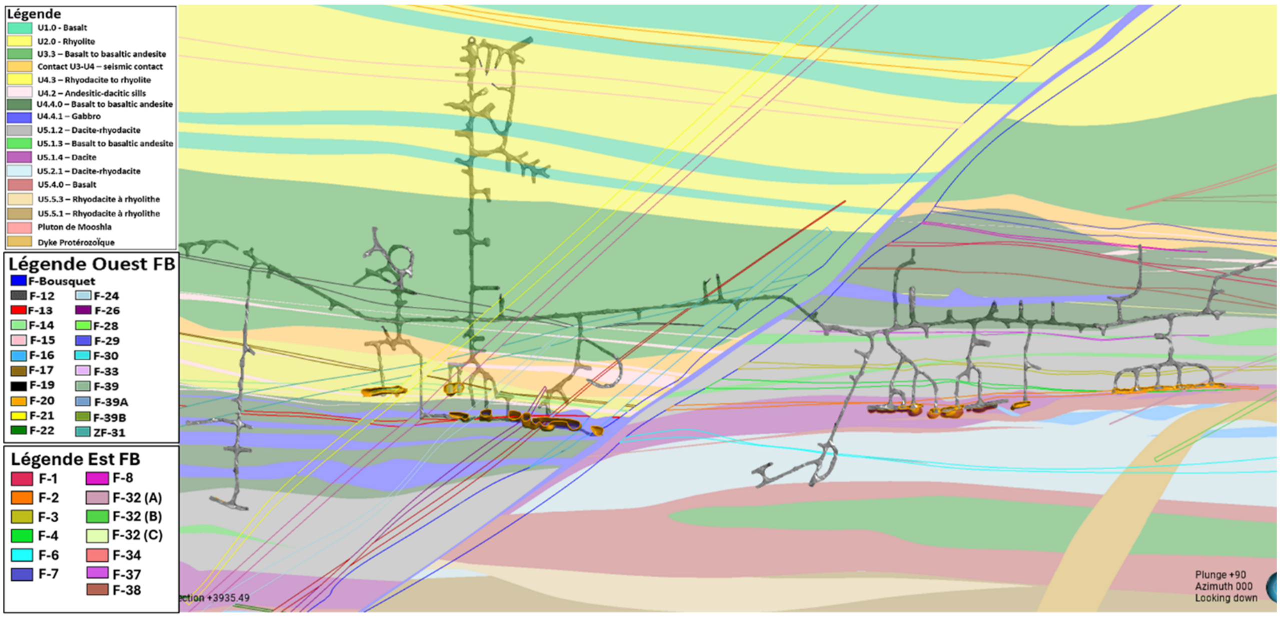


Figure 6 Section view of a typical Westwood sublevel as well as the geological units and major geological structures

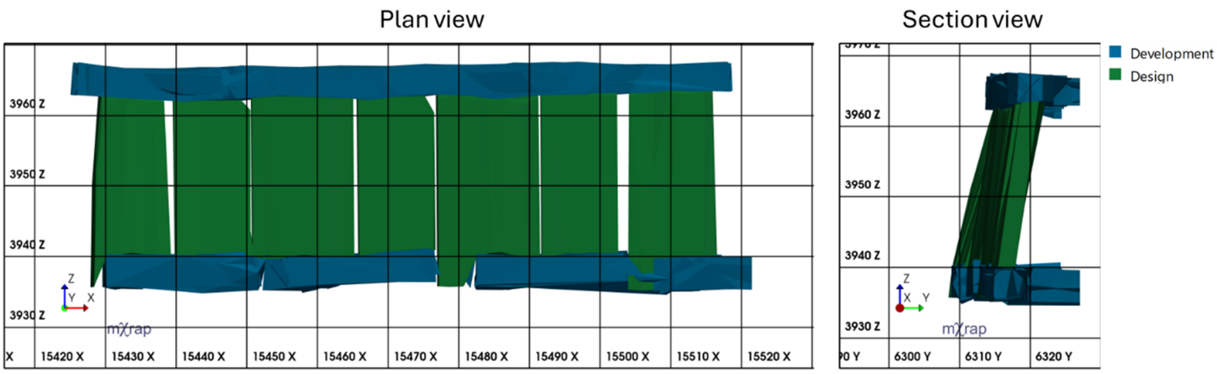


Figure 7 Plan view and section view of a typical stoping area Westwood

4.2 Parameters and data source

The basic data for each stope consists of stope design geometry, mined CMS and the borehole blast design. Development surveys and geological interpretation of major structures in the vicinity of each stope were also incorporated. This data is typically available for all mine sites and is subject to common quality considerations.

A geotechnical block model that characterises geological strength index (GSI), RQD, uniaxial compressive strength (UCS), and UCS contrast was created from the unification of two existing block models. Site engineers built and validated the first 4 × 4 m block model which includes RQD and GSI (which consider the alteration, schistosity and structures) using a kriging method from geotechnical logging of boreholes and underground mapping. The data doesn’t distinguish the different directions of the boreholes and in part utilises older borehole data which lacks quantitative measures. Where necessary, the data is extrapolated from qualitative information. The second block model was also populated using the kriging method and includes the UCS and the contrast UCS. For the WW28 area, the data sampling per block varies greatly from two samples from a single borehole to 20 samples from 12 boreholes. The UCS values are estimated from geochemistry analysis of the rocks based on a general trend found between UCS values and X-ray fluorescence measures for around 100 samples (Martel & Tremblay 2023). Rather than precise values, these estimated UCS values are used by the mine site to typify general fluctuation of the rock strength. The contrast in UCS represents the difference between the selected block's UCS value and the UCS value of the adjacent block to the north. The north–south direction is used as it is the direction perpendicular to the lithology and foliation, which are the main controls of the UCS spatial variation.

4.3 Model information

The entire stope database compiled in the mXrap app is comprised of 219 stopes mined from 2014 until 2023 and are from different mining areas. It can be necessary to separate mining sectors as the impact of each parameter will vary with factors such as the geological setting or the mining approach. The model building process separates the data into two groups following the mining sequence. Each stope underwent general quality filtering, excluding volumes associated with development drives, backfill and muckpiles. Stopes are excluded if there are significant data quality issues such as missing drill rings or an incomplete CMS.

The analysis will focus on the WW28 and the Z226A areas of mining. The WW28 area has 40 longitudinal stopes which are used to build the predictive model and have been mined using the same stoping method and have a similar geological setting. The database consists of approximately 200,000 octrees blocks at a resolution of 0.4 m^3. The Z226A area has 19 stopes which are used to build the predictive model The database consists of approximately 110,000 octrees blocks at a resolution of 0.4 m^3

4.4 mXrap – mining cycle integration

The mXrap app is currently used on a relatively short-term timescale with analysis occurring around three months before a stope is mined.

This involves completing the design section of the reconciliation app which adds a designed stope to the apps database. The performance of the stope design is then predicted using a model trained from similar previously mined stopes. Dilution surface is generated using a 75th percentile threshold which has been selected from the calibration of previous predicted and observed volumes.

Dilution surface is provided to the planning department for economic analysis for their stope book (general notes). The predicted dilution is used to assess the stopes economic viability. This informs if additional actions need to be taken to mitigate poor performance. This might include using ground support (cable bolts) or refining the design geometry. If the stope is economically viable following the considered mitigation, the mining cycle proceeds with planning the practical aspects extracting the stope.

Mining may not proceed if the stope isn't economically viable, and mitigations aren't likely to be cost-effective. Additional geotechnical considerations may also dictate if the stopes are mined, for example, to avoid leaving pillars in the middle of a stoping block which is undesirable in a seismically active mine.

The final reconciliation is completed in mXrap once the stope is mined, and the void surveyed. The performance of the stope is compared with the previously predicted performance.

5 Results

5.1 Multivariate analysis

A multivariate analysis approach at an octree resolution has enabled a thorough root cause analysis of the longitudinal stope's OB and UB in the WW28 and Z226A areas. The multivariate analysis was conducted using a selection of geometrical, geomechanical and operational parameters to understand their relationship and identify the controlling factors. A detailed analysis and discussion of results can be found in previous work (McFadyen 2024) hence only a summary of this work will be provided here.

The multivariate analysis conducted revealed various relationships among the parameters. Statistical correlations do not necessarily indicate dependencies and an understanding of rock mechanics in the context of the mining environment is needed for interpreting the results.

In summary, multivariate analysis of the longitudinal stope OB and UB provided the following key insights:

- OB tends to be observed when the following parameters increase:
  - The blasting energy proxy (based off the density of blastholes around the octree).
  - Effective radius factor (ERF) (towards the middle of the face).
  - Undercut/overcut of the hanging wall and footwall by the drives.
  - Distance to the drifts.
  - UCS contrast.
- OB tends also to be observed when the Distance to fault decreases
- UB tends to be observed near:
  - borders of the faces (small ERF)
  - diminished blasting energy proxy
  - diminished undercut.

The goal of the root cause assessment is to identify the critical parameters that control the stope performance to minimise error associated inherent with predicting stope performance. The critical parameters decreasing in importance that were identified for predicting the stope geometry at Westwood were:

1. undercut
2. ERF
3. blasting energy proxy
4. dip of the face
5. blasting orientation
6. RQD
7. UCS contrast
8. direction of the face
9. distance to fault.

5.2 Predictive modelling

Westwood uses longhole stoping with a pillarless sequence. Dilution is therefore a significant issue for the economic evaluation of a stope. Because of the geological and structural complexity of the Westwood mine, it was difficult to predict stope dilution. While dilution can be calculated in different ways, at Westwood, Equation 1 defines dilution:

$$Dilution\ (\%) = \frac{Overbreak\ Rock\ Volume}{Recovered\ Volume} * 100 \quad (1)$$

To perform the economic evaluation of a stope, an arbitrary average dilution across the entire mine was applied per zone and is refered to life of mine (LOM) dilution. Depending on the sectors, these dilution values could have significant differences, resulting in a stope that was initially economical becoming uneconomical.

After back-analysis, the surface threshold predictions of 75% were the most representative of the actual dilution results for both; WW28A and Z226A. The prediction results obtained for WW28A are very revealing, with an average error percentage of 5% between the CMS values and the predicted value. The level of confidence in predicting dilution for this zone is therefore high. The results of these stopes are provided in

Table 1. An example of predicted projected distance at a 75% surface threshold and observed stope performance is shown in Figure 8.

Table 1 Cavity monitoring system (CMS), life of mine (LOM), and predicted dilution results for the WW28A mining area

Zone	Level	Block	CMS	LOM dilution		70% dilution surface thresholds		75% dilution surface thresholds	
			Dilution%	Prediction%	Error%	Prediction%	Error%	Prediction%	Error%
WW28A	132-07	144	94	90	4	80	17	94	1
WW28A	132-08	144	97	90	7	90	7	103	6
WW28A	132-07	143	124	90	37	106	17	125	1
WW28A	132-07	145	170	90	89	142	20	161	6
WW28A	132-07	146	121	90	35	105	15	119	2
WW28A	132-06	144	178	90	97	132	35	153	16
Average			**131**	**90**	**45**	**109**	**18**	**126**	**5**

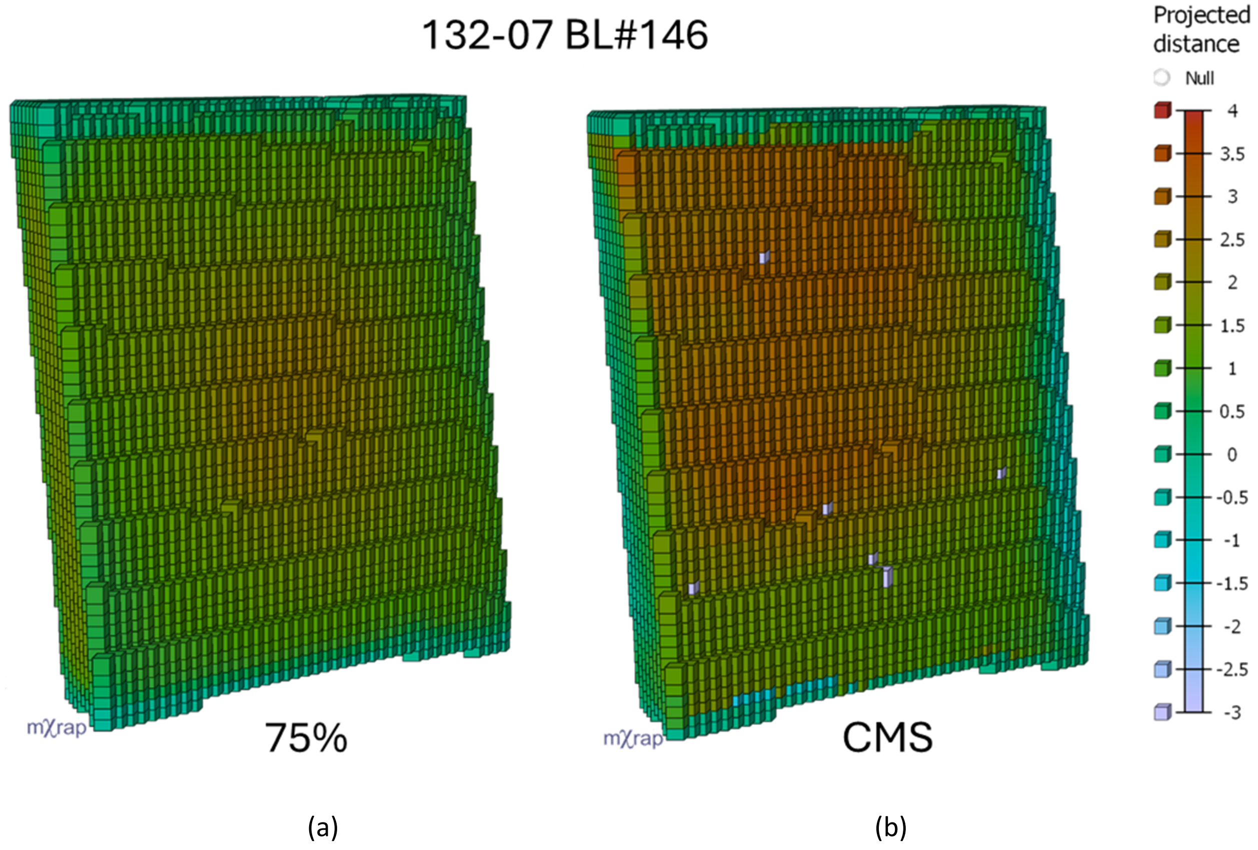


Figure 8 Projected distance (m) for stope 132-07 BL#146 in WW28A zone for the (a) 75% prediction threshold surface and (b) the cavity monitoring system (CMS) surface

For Z226A, the average error percentage is higher, at 40% error, which is better than the average error percentage with the values used in the LOM, which is an average of 60% error for stope dilution. The results of these stopes are provided in Table 2. An example of predicted projected distance at a 75% surface threshold and observed stope performance is shown in Figure 9.

Table 2 Cavity monitoring system (CMS), life of mine (LOM), and predicted dilution results for the Z226A mining area

Zone	Level	Block	CMS	LOM dilution		70% dilution surface thresholds		75% dilution surface thresholds	
			Dilution%	Prediction%	Error%	Prediction%	Error%	Prediction%	Error%
Z226A	132-05	038	41	60	31	57	27	66	37
Z226A	132-05	037	57	60	4	48	20	56	3
Z226A	132-05	036	118	60	97	63	89	76	55
Z226A	132-05	035	179	60	198	94	90	109	64
Z226A	132-06	038	35	60	41	58	39	67	47
Z226A	132-06	039	62	60	4	62	0	76	18
Z226A	132-06	037	31	60	48	63	51	72	57
Average			**75**	**60**	**60**	**64**	**45**	**75**	**40**

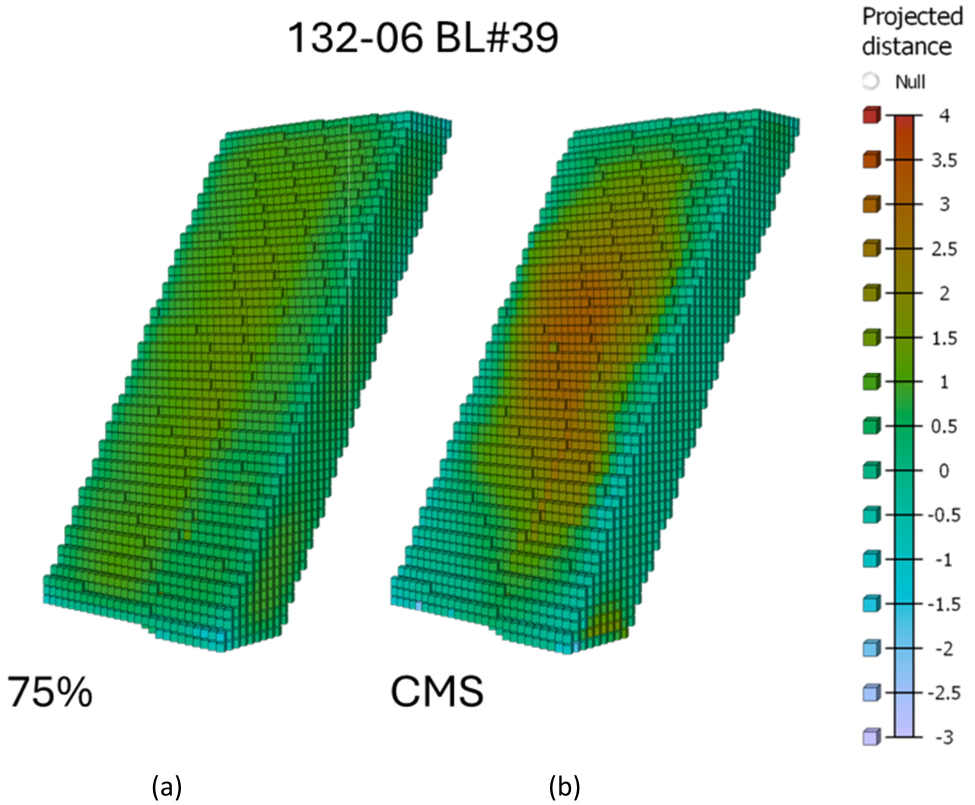


Figure 9 Projected distance (m) for stope 132-05 BL#37 in Z226A zone for the (a) 75% prediction threshold surface and (b) the cavity monitoring system (CMS) surface

6 Discussion

Multivariate analysis revealed various relationships among the independent parameters and identified the critical parameters that control stope performance. These trends are consistent with what is intuitively expected, e.g. higher blast energy results in more OB. Additionally, the general trends observed are consistent with root cause analysis conducted for other sites. This analysis assists in understanding the parameters being used for predictive modelling and inherent associated error. This analysis has practical outcomes when designing a stope during the mining cycle by highlighting what areas of the design process can be targeted to maximise stope performance while minimising costs associated with excessive UB and OB. At Westwood, the critical factors are undercutting (#1), ERF (#2), and dip of the face (#4). Any redesign of stope geometries should, where possible, minimise undercutting, reduce the stope span, and avoid shallow dipping faces. Where options for design geometries are constrained then these factors may be partially controlled by cable bolts. Blast design which is directly related to blast energy proxy (#3) and blast orientation (#5) highlight the influence that blast design has on stope performance and is often a more flexible mitigation tool in comparison to modifying stope geometries which are constrained by orientation of the mineralisation and the mining method.

Stope reconciliation was tested in two zones in the mine: Z226A and WW28A. Each zone was treated separately due to their depth as well as their distinct geological and structural context. Back-analysis were performed on Z226A and WW28A. For each back-analysis, drilling data provided by the drilling-blasting team, planned stope geometry, geological and structural models, and certain geotechnical parameters including RQD, Q' index parameters, and the UCS block model entered into the application. These data were used in the planning phase and for stopebooks, primarily in economic evaluation and assessment of mitigation measures to reduce this dilution (cables, geometry, etc.).

In contrast to root cause analysis which captures general trends and inform broad aspects of the stope design process, measures of predicted performance can be considered as a testable hypothesis. This is an important aspect of the methodology as stope predictions can be evaluated against observed performance to validate results. Discussion is limited to the most basic comparison of predictions and observations due to the novity of this approach.

While the 70th percentile results are presented for both areas, in both cases this threshold tended to underestimate dilution. 75th percentile dilution surfaces appear to be a reasonable calibration to ensure the scale of predicted performance and subsequent surface reconstruction aligns with the scale of observations.

WW28A predictions for the 75th percentile dilution surface matched the observed dilution with only 5% error on average. This is a significant improvement on blanket LOM estimate which has 45% error on average. In contrast, the Z226A 75-percentile dilution surface predictions were less accurate although still have less error (40%) on average compared to the LOM estimates (60%). The average dilution observed matching the average predicted dilution is likely a coincidence given the variability in errors for individual stopes.

The increased error may be explained by the predictive model being trained with less data along with factors such as the levels of alteration in the rock mass which vary with depth in Z226A area, operational difficulties related to drilling and blasting, the mining sequence, and additional ground stress related factors not currently included in the predictive model.

7 Conclusion

Stope reconciliation was found on site to be a useful tool to predict the expected dilution for a stope. The new proposed design approach enabled the prediction of stope performance at an octree level. This means the location and magnitude of OB and UB were predicted, allowing the user to visualise the expected CMS in 3D and calculate volumes of OB and UB from it.

The approach to stope reconciliation in mXrap is a significant leap forward from current industry practice. The benefit of this approach is underpinned by the ease of developing and maintaining an extensive stope database that quantifies performance and controlling factors on a per octree scale. The comprehensive nature of this data enables an improved understanding of the root causes of OB and UB along with a probabilistic approach to predictive modelling. Integrating an economic assessment of predicted stope shapes with an iterative approach to optimising stope design provides more accurate and precise estimates of future mining. Improved estimates of expected performance have corresponding benefits to LOM planning and assessing the viability of individual stopes and along with the opportunity to optimise stope designs, the stope reconciliation tools in mXrap offer a pragmatic method to maximise the value realised from mining operations.

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