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The role of the geotechnical model for rapid integration in managing operational geotechnical risk

MC Brockman *AngloGold Ashanti Australia Ltd, Australia*

KMR Gosche *AngloGold Ashanti Australia Ltd, Australia*

DJ Du Plooy *AngloGold Ashanti Australia Ltd, Australia*

Abstract

AngloGold Ashanti (AGA) has developed a concept to integrate geotechnical input into long-term mine planning using a 'block model approach' referred to as a geotechnical model for rapid integration (GMRi). The GMRi is a simple spatial collection of rock mass data integrated with empirical evaluations, numerical modelling results and monitoring data for a specific mine plan. In this paper, the value of using the GMRi to manage geotechnical risk and identify opportunities associated with ground support design, stress-induced damage, design stope spans and total extraction is demonstrated. The GMRi concept allows for the rapid evaluation of spatially distributed geotechnical data and identifies areas of risk and opportunity, demonstrated at two recent underground studies completed at AGA's Australian operations.

Keywords: *rock mass model, geotechnical block model, GMRi, geotechnical risk management*

1 Introduction

A geotechnical model for rapid integration (GMRi) allows the visualisation of data in 3D space. This data can easily be manipulated and engineering parameters added, as needed, to build a highly customisable block model for geotechnical input into mine design. The spatial representation of the geotechnical data allows for areas of differing ground conditions or failure mechanisms to have the appropriate design guidance to manage operational and investment risk.

Models have been built for AngloGold Ashanti (AGA) Tropicana Gold Mine (TGM) and Sunrise Dam Gold Mine (SDGM). The two operations are at different stages of operation, with TGM exploring opportunities for an underground operation and SDGM being a well-established underground operation with a wealth of geotechnical rock mass behaviour understanding and established design criteria. The GMRi concept has been applied in both cases to provide input into mine planning and design to ensure areas of geotechnical risk and opportunity are recognised and managed.

2 Geotechnical risk factors

With the two operations currently investigating the feasibility of underground expansion projects, it is essential that a robust framework is established to evaluate all potential geotechnical risk factors. These are generally determined through a process of identifying the major 'drivers' influencing the geotechnical design, which include:

- Stability of access ways and long-term infrastructure development.
- Stope stability, design and dilution estimates.
- Pillar stability and design.
- Stability associated with large-scale geological structures.
- Optimal extraction ratio.

3 Developing the GMRi basis

The geotechnical model requires spatially representative data over the design area. The input data needs to have adequate quality and density for the required level of application to evaluate geotechnical risk. Rock mass data may be interpolated from drillhole or mapping data in the case of rock mass characterisation and classified or evaluated by numerical modelling of stress state inputs considering mining design. For the correct application of the GMRi, the correct geotechnical data inputs to evaluate the drivers behind geotechnical design need to be adequately represented over the design area.

3.1 Available input data

Evaluation of the geotechnical risk requires the correct inputs for various analysis techniques relevant to design. For the underground operations, a GMRi requires the following inputs to be spatially representative:

- Rock tunnelling index Q (Barton et al. 1974).
- Rock mass strength, uniaxial compressive strength (UCS).
- Stress state and its redistribution around mining shapes using boundary element method.
- Rock mass structural data.

A more established operation has calibrated a back analysed design criteria from underground inspection data used to predict stress-induced damage.

3.2 Rock mass model

A well-constructed rock mass model, similar to a typical ore resource model, forms the basis for the development of a GMRi (Hamman et al. 2017). Rock mass characteristics from geotechnical core logging and underground mapping, where available, were converted to describe the rock mass in terms of Barton's Q classification (Barton et al. 1974) and a calculated UCS from equotip testing.

Leapfrog Geo (Sequent 2018) was used to interpolate the rock mass data using a spheroidal interpolation and a structural trend to construct a representative rock mass model. The structural trend for each model used the orebody foliation and large-scale structures (shears and faults) to honour the orientation of the geotechnical environment. For the interpolation, Q was calculated from the raw rock mass data prior to interpolation to best represent rock mass quality accurately at each location. The interpolated data was evaluated for a 10 × 10 × 10 m grid assigned to the GMRi in Excel formats (.csv and. xls). The spacing of the grid (10 m) will determine the resolution of the GMRi, which needs to be appropriate for the design area and data density. Each row in the Excel GMRi represents a point of the grid and has x, y, and z coordinates and a value for the interpolated input data. As the GMRi develops, columns are added containing new engineering parameters for each row from calculations of the input data.

The GMRi grid is constructed in GEM4D (Basson 2018) to be spatially representative over the design area and is typically used to colour development (Figure 1) and stoping triangulations (Figure 2) that allows the end user to develop an understanding of the spatial distribution of rock mass quality. At a preliminary level, this highlights areas of expected poor ground conditions and gives the opportunity for development to be redesigned or an assessment of the risk.

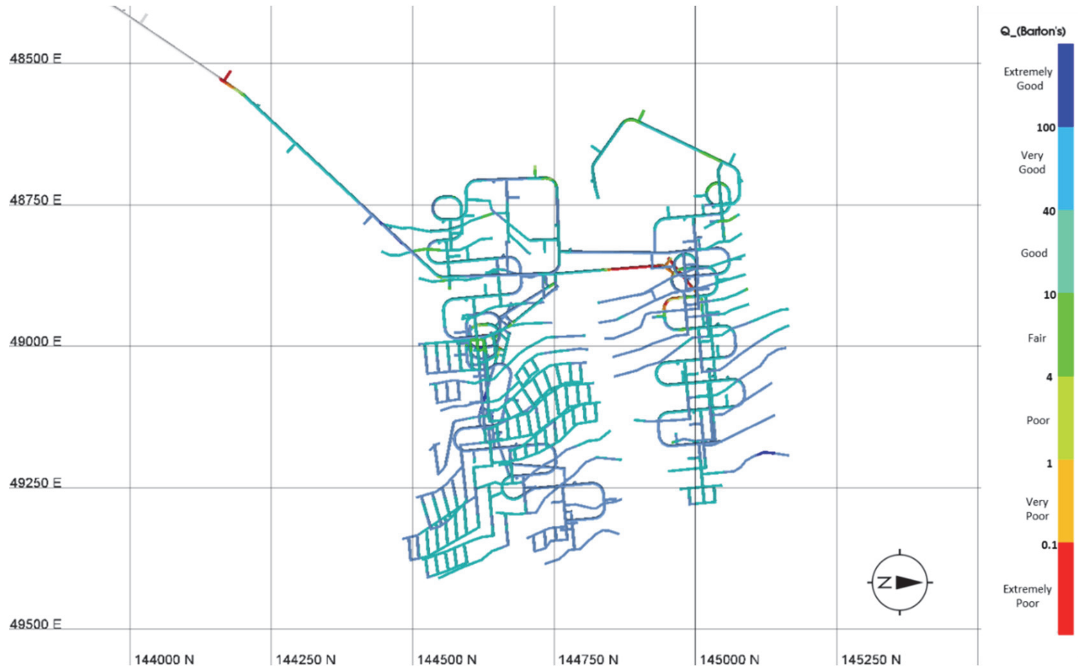

Figure 1 Barton's tunnelling index Q represented over the underground mine development design

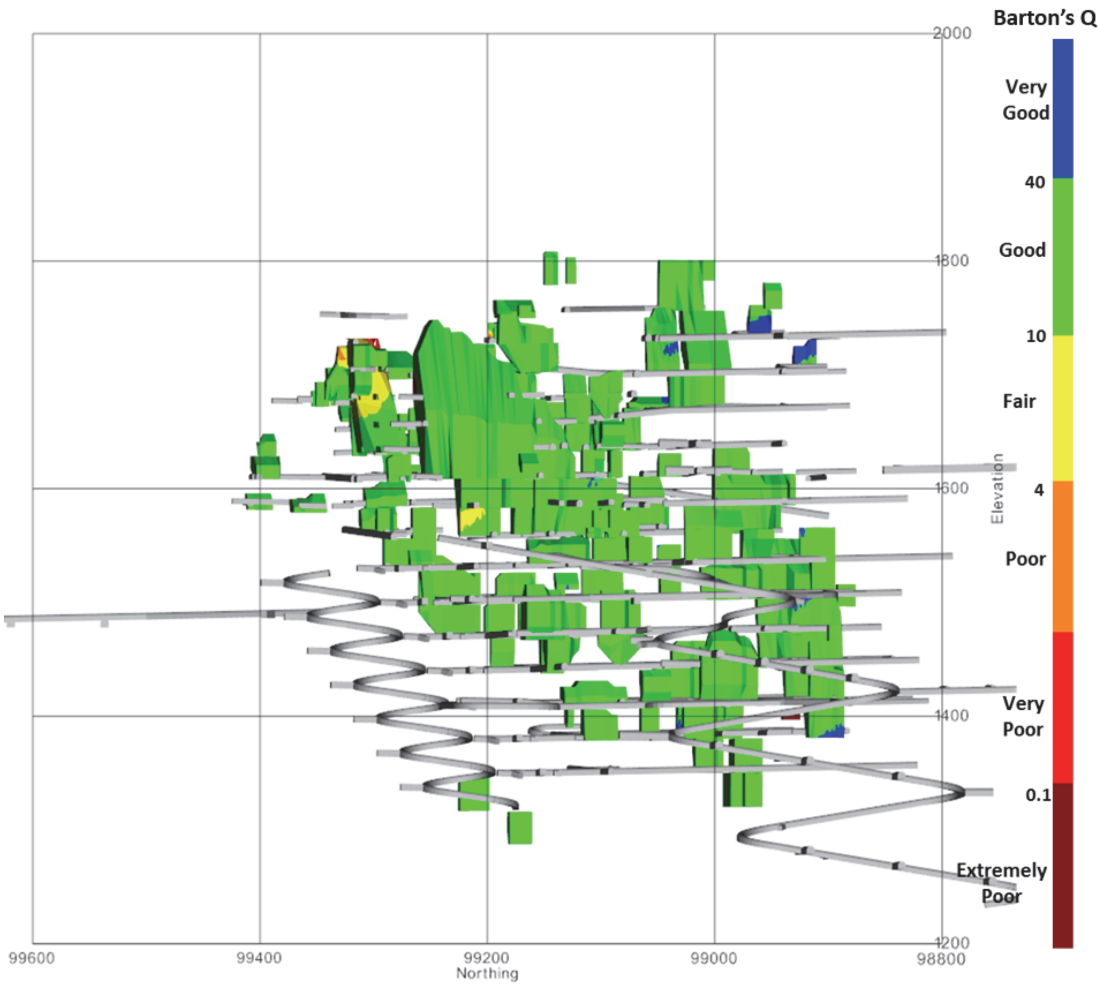

Figure 2 Barton's tunnelling index Q represented over stoping design shapes

3.3 Numerical stress model

A simplified elastic stress model was developed for each operation by utilising a boundary element program, Map3D (Wiles 2018). The model focused on the redistribution of stress around the designed stoping shapes. Mining-induced major principal stress (σ_1) and minor principal stress (σ_3) were modelled for the scenario of all stopes extracted using three mining steps (pit mined, previous underground stopes mined, and design stopes mined). The results were calculated on points corresponding to the GMRi points and subsequently integrated into the geotechnical model. In areas where stope wireframes and GMRi points are in close proximity, anomalous results may occur, due to extreme stress conditions modelled at the stope boundary. Due to this effect, GMRi points within a set distance from stoping wireframes (1 m) are excluded to negate their influence on results.

3.4 Geotechnical domains (structural data)

Structural data is collected spatially with drill core structural measurements, acoustic televiewer (ATV) and, where available, structural mapping. The spatial variance of structural data in the design area is critical for understanding structurally driven failure mechanisms. Domaining of the structural data is completed to group areas of similar structure orientations and ensure the appropriate design parameters are applied. For stope span stability, the orientation of the structural set critical to the stope span will be a determining parameter for maximum design span. The domaining of the structural data, separated by large-scale shear structures, is shown in Figures 3 and 4.

At pre-feasibility stage, the structural data showed limited variation (and a drillhole bias in Figure 3), as mapping data was not available.

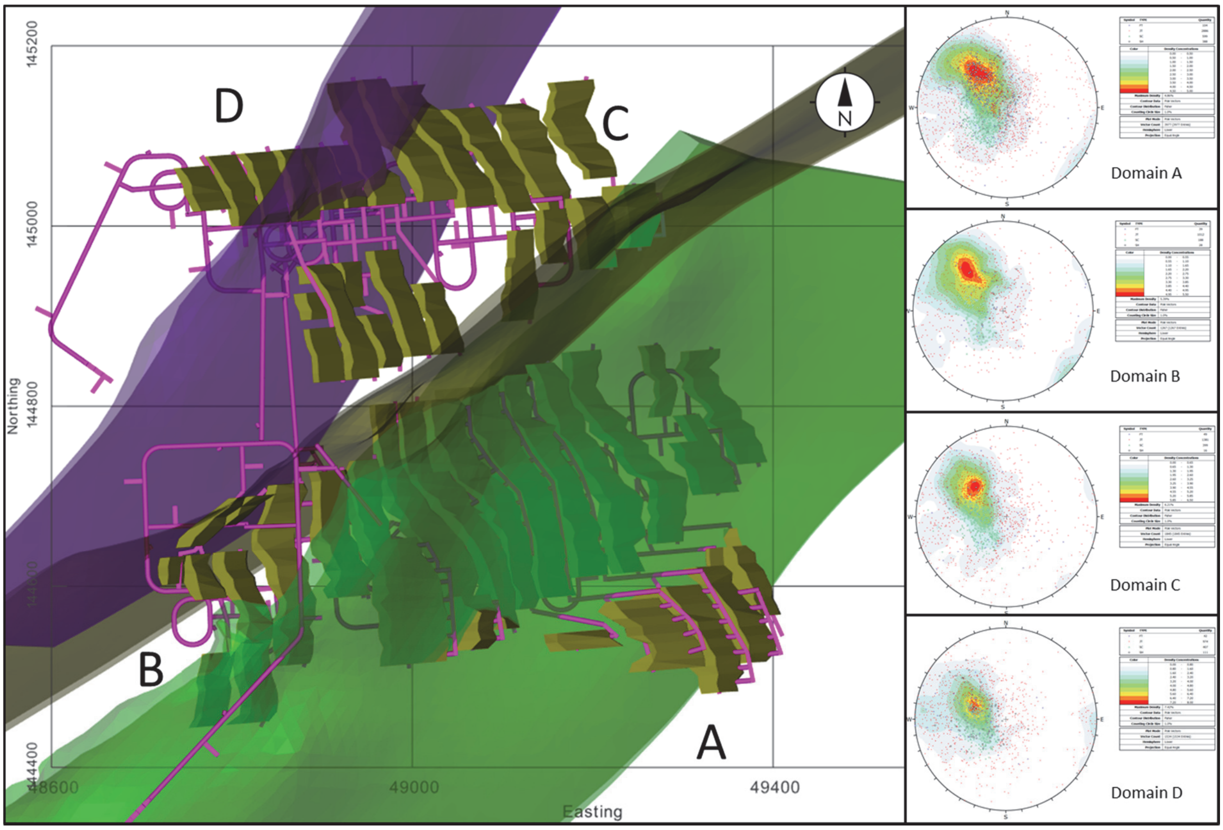

Figure 3 Rock mass structural domaining of the underground mine, based upon large-scale shear structure (warmer colours indicating high structure population in stereonets)

For the established mine, development near the area of study was accessible to perform underground mapping. The mapping data was combined with the major modelled geological shears to establish three domains as shown in Figure 4. All domains had similar dominant or critical orientation (sub-parallel to the shear) which is characteristic of the mine overall. The major difference applied to each domain was the number of joint sets used in determining Q.

The structural domains are incorporated into the GMRi with a 'Domain' column, which allows the data to be filtered for viewing. It also facilitates the incorporation of 'if' statements for the application of parameters specific to the domain (critical orientation, number of sets, etc.) to be used in the calculation of design criteria.

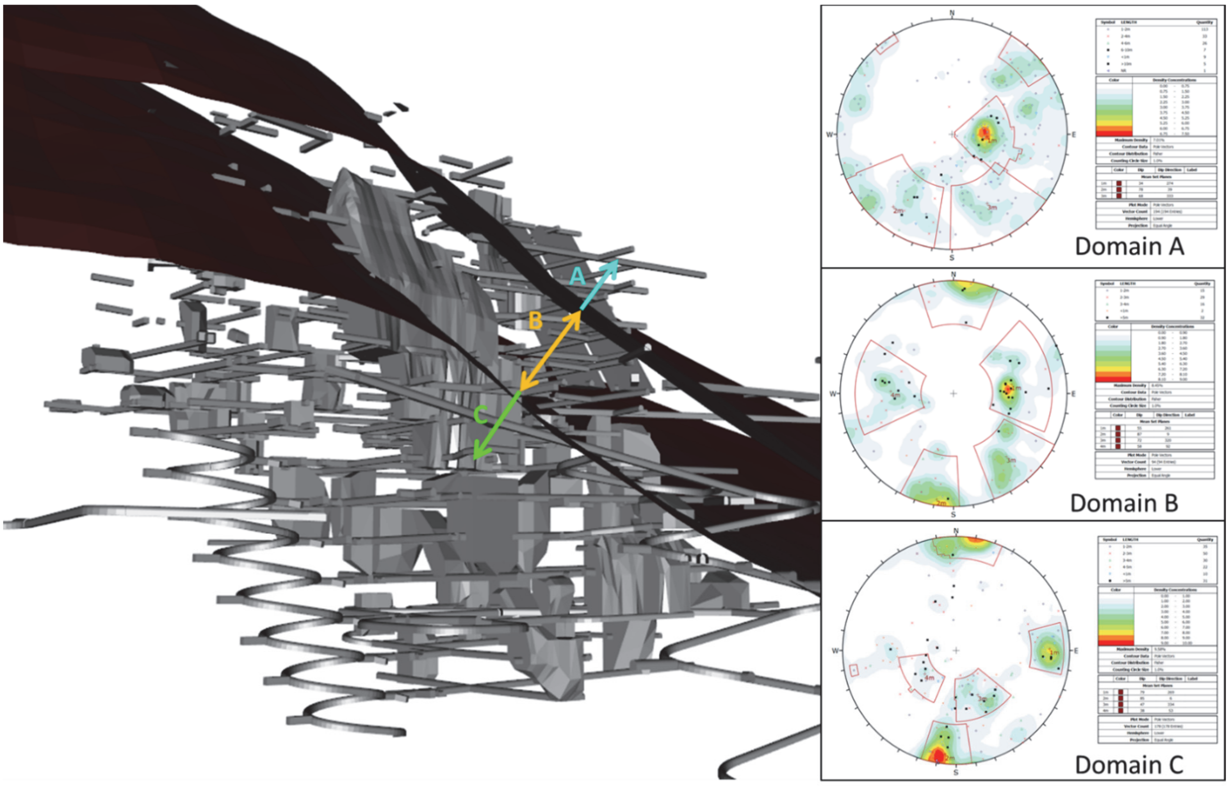

Figure 4 Rock mass structural domaining of the established operation using underground mapping data obtained from existing development (warmer colours indicating high structure population in stereonets)

4 Mine design parameter integration

Underground stoping design parameters can be calculated and integrated into a GMRi, specific for evaluation of stope and pillar design. In this instance, the GMRi is represented by evenly spaced points along the hanging wall stoping design (still in simple .csv and .xls form) for evaluation as opposed to the generic 10 m spaced grid. The change in the GMRi points setup allows each point (located on the hanging wall) to be relevant to stope and pillar design. The pillar height (orebody thickness) and dip of stope hanging wall are parameters governed by the mine design that are included in the evaluation process. In this case, the GMRi grid is evaluated for both as they are critical to the design process:

- Orebody thickness will dictate the stoping and pillar height. The larger the height, the larger the width (strike span) of the pillar required to maintain stability of the same geotechnical environment.
- Dip of the orebody and therefore hanging wall will be critical to the stope span design. The angle of the hanging wall is compared to the orientation of significant structure sets and the expected failure mechanism to determine the acceptable stope span.

The parameters are accounted for in the GMRi by extracting measurements of the stoping design using GEM4D (Basson 2018). The orebody thickness is determined using a plane (wireframe) of both the hanging wall and footwall with GEM4D determining the distance between them, extrapolated onto the GMRi using the nearest value. The dip of the hanging wall was determined by extrapolating stope hanging wall dips onto the hanging wall points using the nearest value. The result of each interpretation is a set of points, evenly spaced along the stope hanging wall with a value for orebody thickness and stope hanging wall dip, interpolated onto the stope design shown in Figure 5.

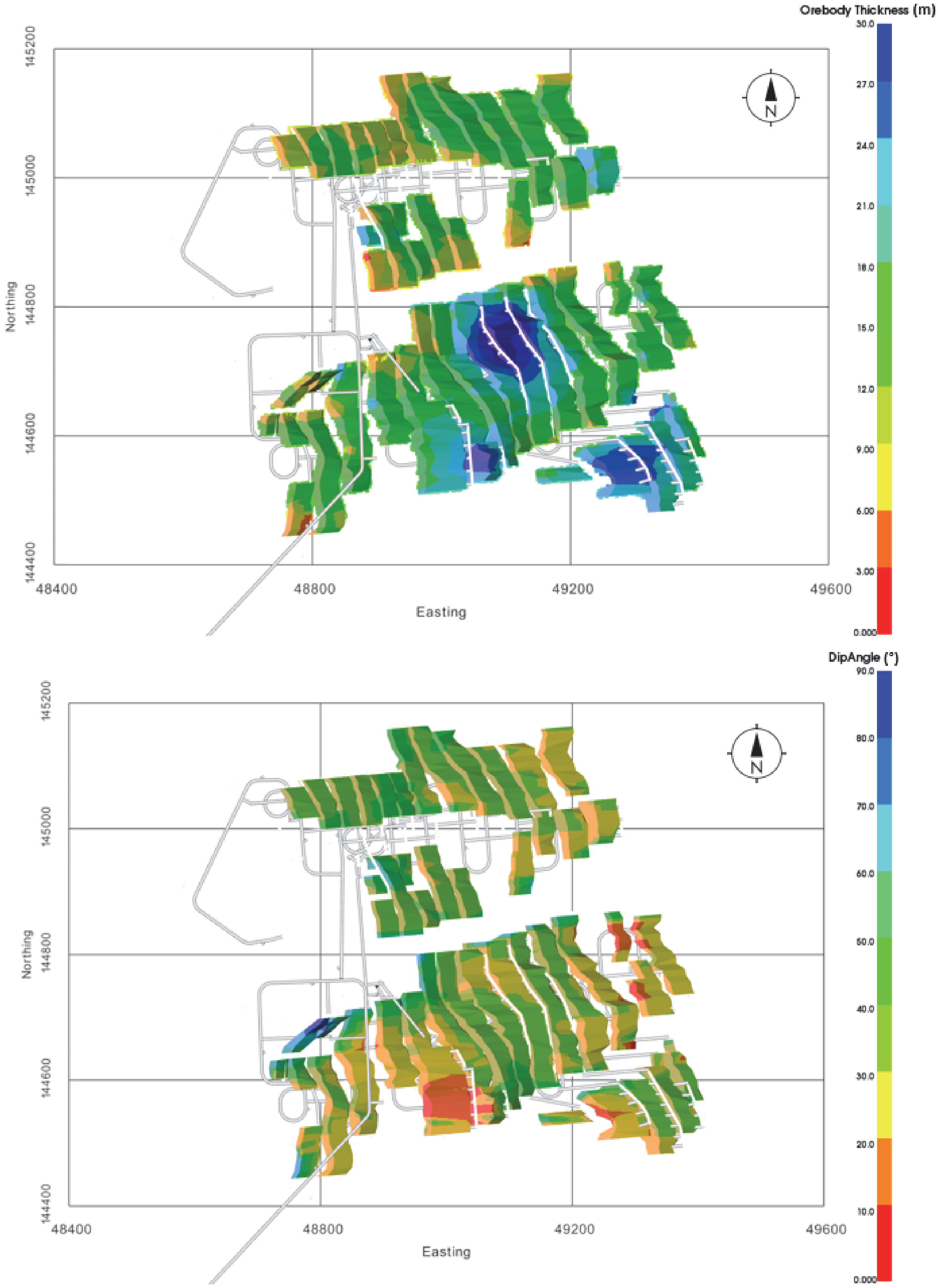

Figure 5 Mine design stoping and pillar parameters (orebody thickness and hanging wall dip) for the underground mine

The nature of the orebody and designed stope shapes for the established operation only utilised the stope wall orientation in the GMRi. Some shapes have large stope crowns that can greatly influence the overall parameters applied to the design. Both the hanging wall and crown orientations have been integrated into the GMRi to allow for precise span and stability evaluations of the actual design conditions. Figure 6 shows the dip and dip direction of the stope faces that have been included in the stoping GMRi for this operation.

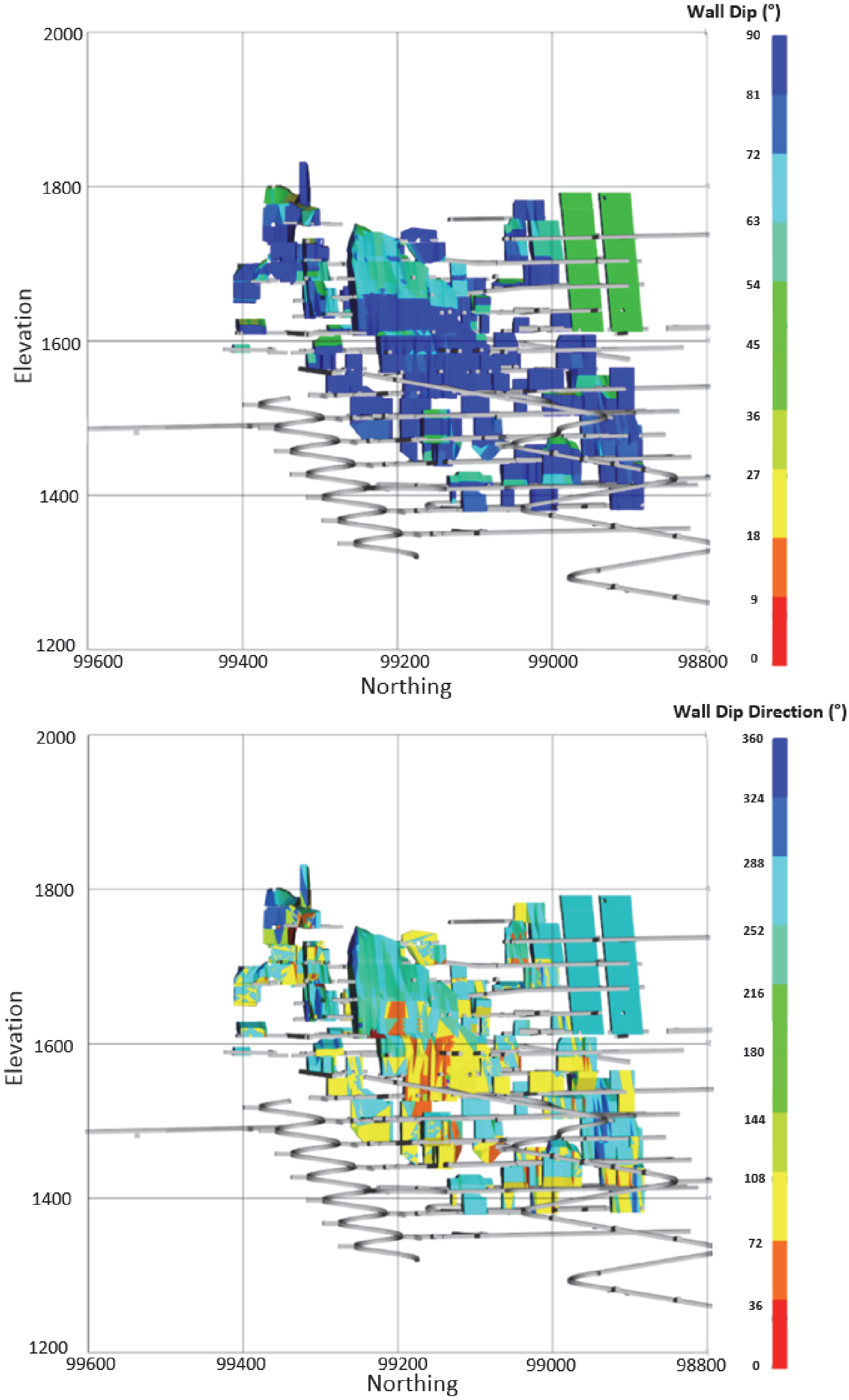

Figure 6 **Mine design stoping shape parameters (wall dip and dip direction) for the expansion of existing mine design**

5 Geotechnical design and application to mine planning

Once the basis for the model and the stope design parameters were integrated into the GMRi, it was simple to add calculations to output geotechnical factors. Values can be based on empirical or theoretical relationships, as well as observed rock mass behaviour. The flexibility within the GMRi allows key geotechnical parameters to be visualised in 3D space to allow for analysis and stoping optimisation.

5.1 Ground support design

The spatially distributed rock mass classification Q can be used to determine preliminary ground support designs. The ground support designs are based upon current industry practices observed in Canada and Australian operations (Potvin & Hadjigeorgiou 2016) and as such, can be used as a sound estimate for ground support designs at pre-feasibility level. The paper concludes a correlation between the rock mass classification system Q and ground support pattern. As the GMRi is in .csv format, a simple 'if' formula was created to convert the Q value into a ground support pattern (bolt density, shotcrete thickness and surface support coverage) as a new column (ground support class):

- $Q > 10$ Class 5.
- $4 < Q \leq 10$ Class 4.
- $1 < Q \leq 4$ Class 3.
- $0.1 < Q \leq 1$ Class 2.
- $0.01 < Q \leq 0.1$ Class 1.

The GMRi provides an estimate of the ground support required and identifies areas where additional support will be required, as shown in Figure 7.

Figure 7 Ground support class for the development of the underground mine

5.2 Stress-induced failure for capital development

A key aspect of geotechnical risk management is the ability to provide some insight into where mining-induced stress may have a negative impact on access development stability. For the two studies discussed here, AGA used two different approaches due to stage of the operations:

1. Rock wall condition factor (RCF) for the new underground operation.
2. Observational correlation with numerical modelling results for the established underground operation.

5.2.1 Rock wall condition factor

The redistributed stress conditions, when compared to rock mass compressive strength, can provide an estimate of the stress-induced deterioration, using Equation 1 (Jager & Ryder 1999):

$$RCF = 3\sigma_1 - \sigma_3 / F\sigma_c \tag{1}$$

where:

σ_1 = major principal stress.

σ_3 = minor principal stress.

F = empirical rock mass condition factor.

σ_c = UCS.

The F factor was inputted into the GMRi to apply an F value of 0.5 for grid points within shear zones and 1 for points outside. The RCF calculated was projected onto the capital infrastructure design to show spatial variation in RCF (Figure 8).

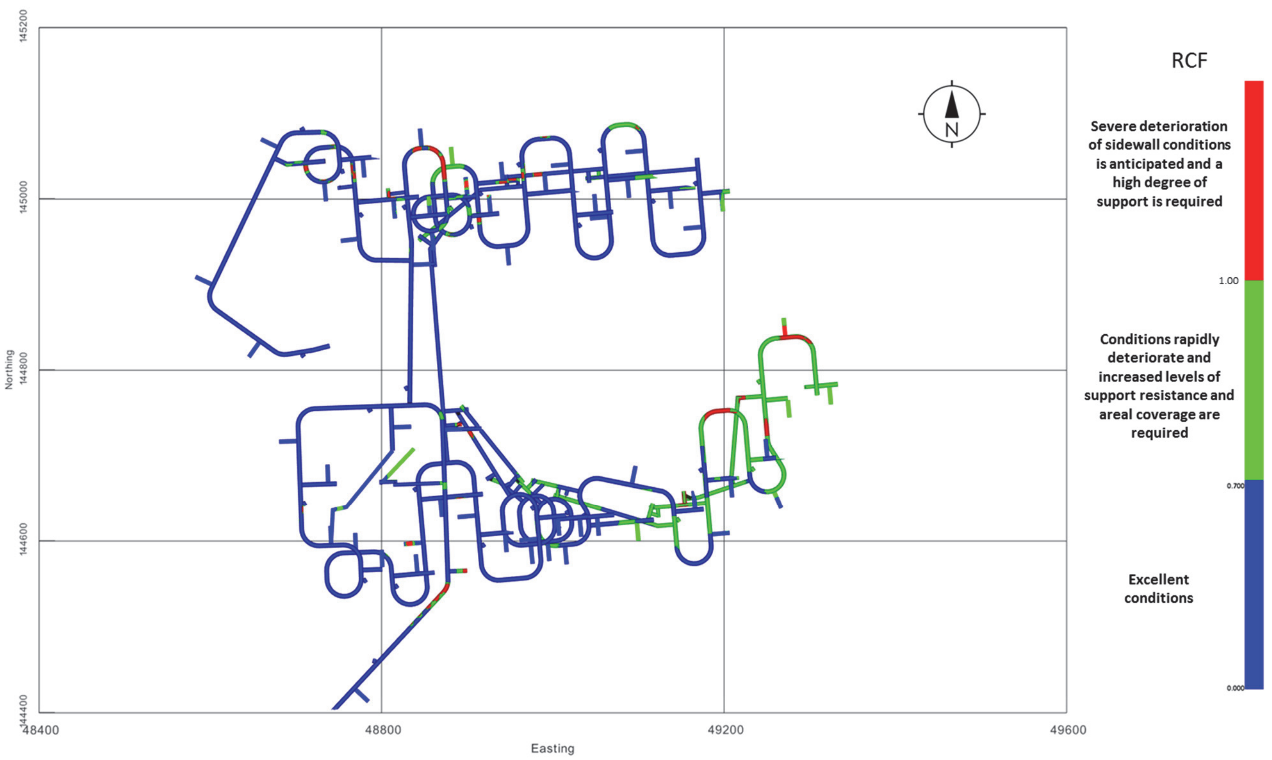

Figure 8 Rock condition factor of capital infrastructure, showing stress-induced damage due to stoping

Figure 8 indicates that the most eastern section of decline is modelled to have increased stress-induced deterioration and was recommended to increase the distance between stoping and the decline to eliminate the risk.

5.2.2 Correlation of observed stress-induced damage with elastic numerical modelling results

Observations of actual ground response to mining activities provides the ability to build on theoretical relationships. A damage criterion for development based on previous levels of support damage and rock mass deterioration has been developed that uses modelled stresses to visually represent zones of damage based on a published damage scale (Sandy et al. 2010). This is integrated into the GMRi by adding a column to calculate the stress for each damage level and then a final column, ‘Stress category’, to classify the stress at each point of the GMRi based on the modelled induced stresses. The stress category can then be projected onto development, shown in Figure 9 for designed life-of-mine development.

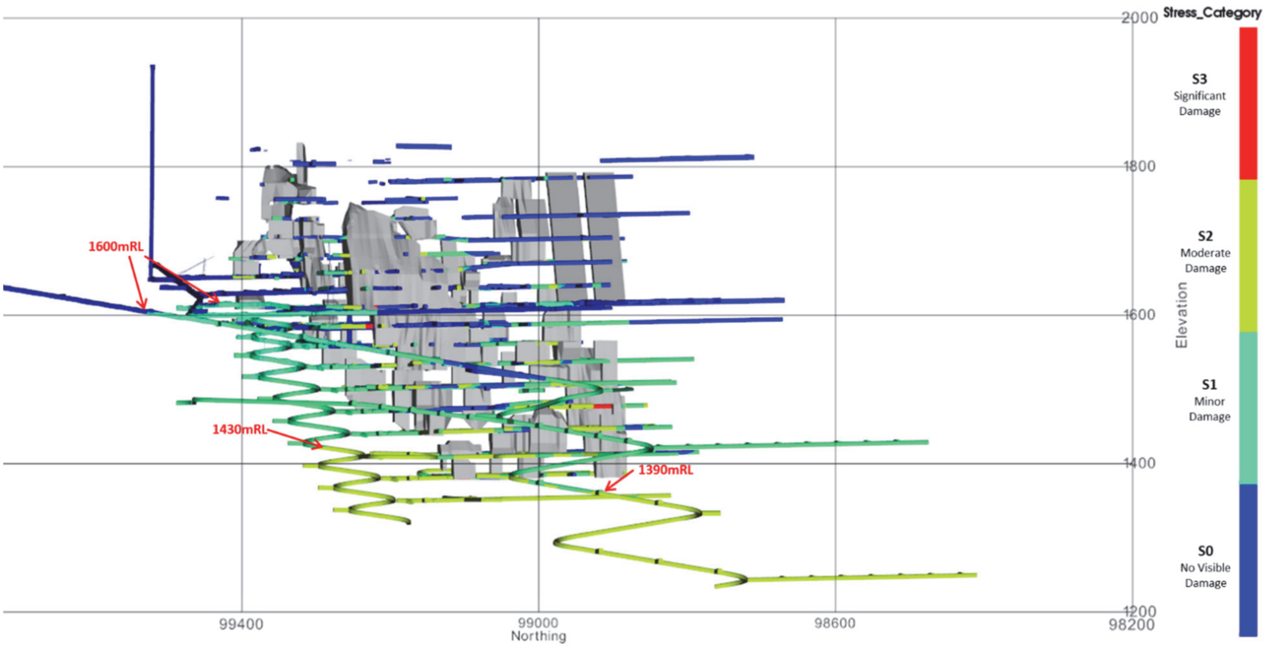

Figure 9 Stress category for life-of-mine development based on the Sandy–Sharrock damage scale and development back-analysis work

Visualising the data spatially allows the identification of areas (generally in close proximity to stopes) where significant damage is expected and provisions for additional support or rehabilitation can be made. It also highlights the potential for fundamental changes in the stress ground response as mining progresses with depth.

5.3 Stoping spans

Stope reconciliation and back-analysis work has led to the development of a site-calibrated stability criteria (Brockman 2014) and updated (Wieben 2016) to specify the maximum hydraulic radius (HR) depending on the acceptable depth of overbreak. The criteria involved three curves (Figure 10) categorised as stable, design, and significant overbreak.

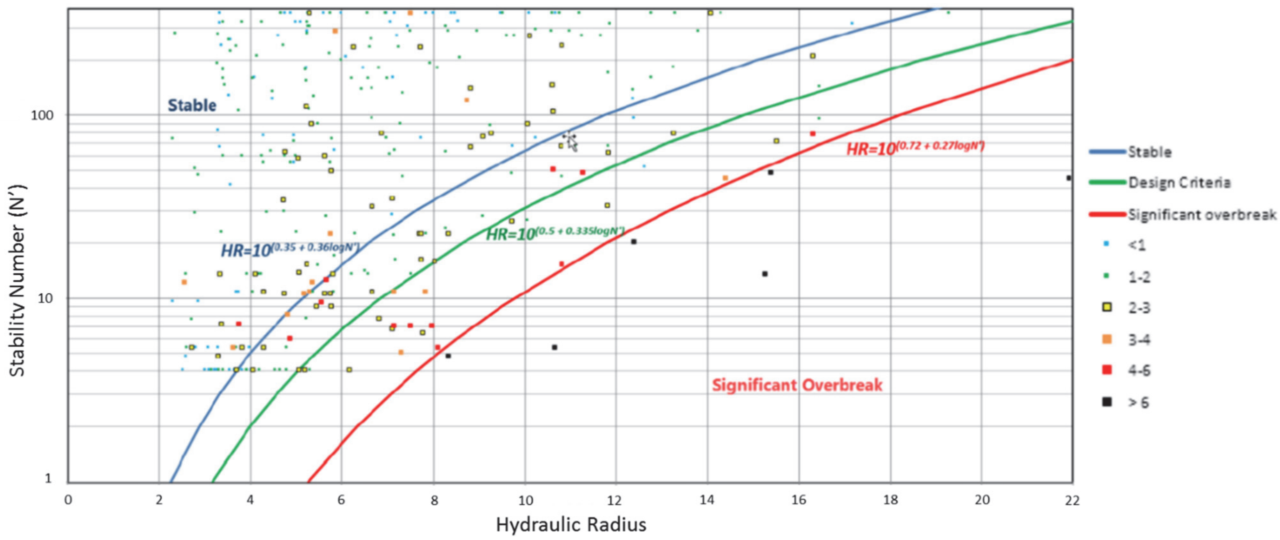

Figure 10 Stability graph for bulk stopes using unsupported spans

Each criteria has been integrated into the GMRi using stope wall orientations, Q' (variant of Q, negating the influence of stress and water conditions), and dominant structural orientations to visualise the HR for each criteria in 3D space.

To evaluate the maximum HR for each curve, the modified stability number (N') is calculated using Equation 2 (Mathews et al. 1981):

$$N' = A \times B \times C \times Q' \tag{2}$$

where:

A = rock stress factor.

B = joint orientation factor.

C = gravity adjustment factor.

Q' = modified rock quality index.

A column is added to the GMRi for the A, B, and C factors and each factor is calculated specifically for the orientation of each point in the GMRi. The above formula calculates N' and then site specific criteria of HR values (shown on the graph below) for each point in the GMRi. The stope shapes can then be coloured for stable, design or significant overbreak HR is dependent on design requirements by projecting calculated values of the GMRi onto the stope wireframes. As an example, the maximum HR to achieve the design criteria is shown in Figure 11 and similar visualisations are easily created for each criteria.

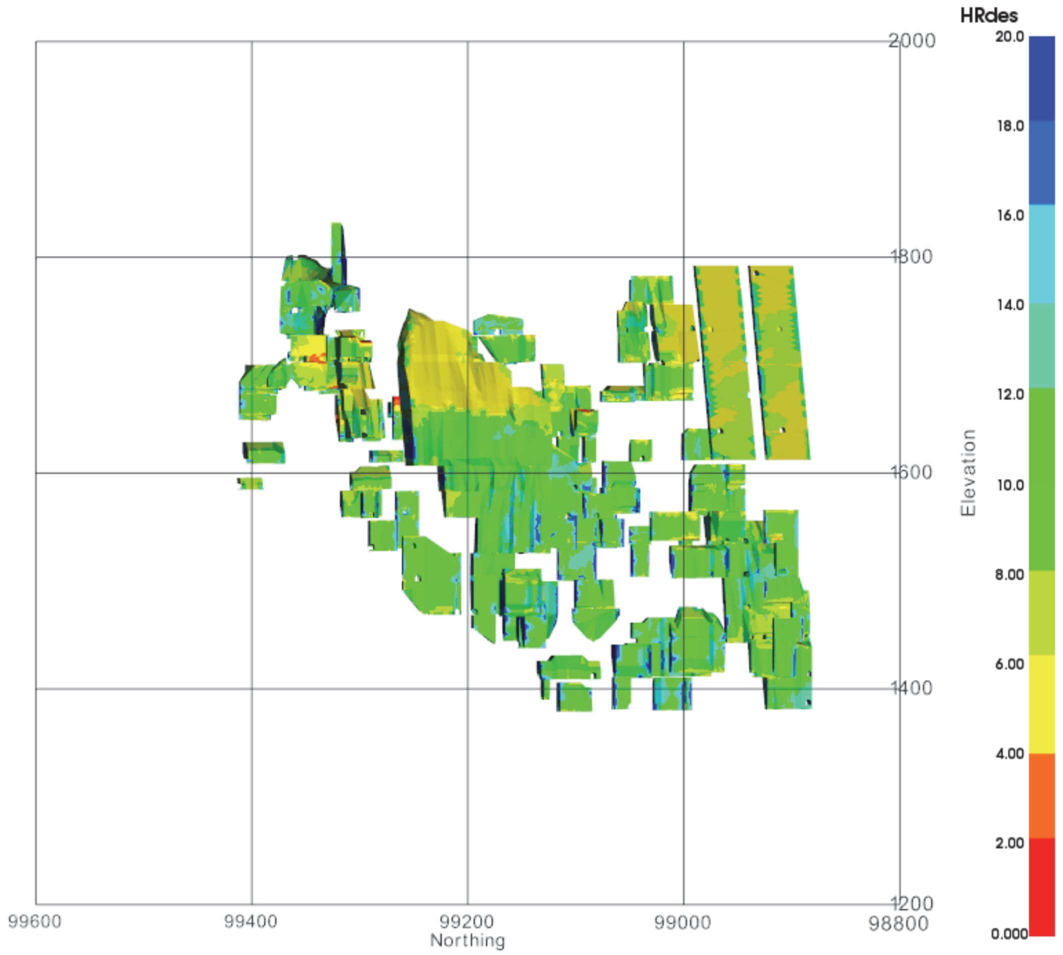

Figure 11 **Design hydraulic radius (HR) for design stope hanging walls from stability graph criteria**

This information is provided to the strategic planning team to optimise stope designs based on the expected acceptable span.

5.4 Depth of failure for designed stopes

As the modelled induced stresses around the stoping shapes are incorporated into the GMRi, a stress calculated from design criteria at each point of the GMRi can be calculated in a separate column. If the modelled induced stress exceeds the design criteria stress, the overstressing mechanism (Wiles 2007) would be expected in the area. To represent this in the GMRi, the design criteria stress is subtracted from the modelled induced stress to introduce an 'Excess stress' column. Each x, y, and z point within the GMRi contains this information, allowing areas where the design criteria is exceeded (negative values) to be readily viewed. The spatial representation of this information also allows the creation of failure shapes and depths as shown in Figure 12. The shapes are estimated using an iso-surface around the zones of zero excess stress, which would correspond to the induced stress equalling the design criteria.

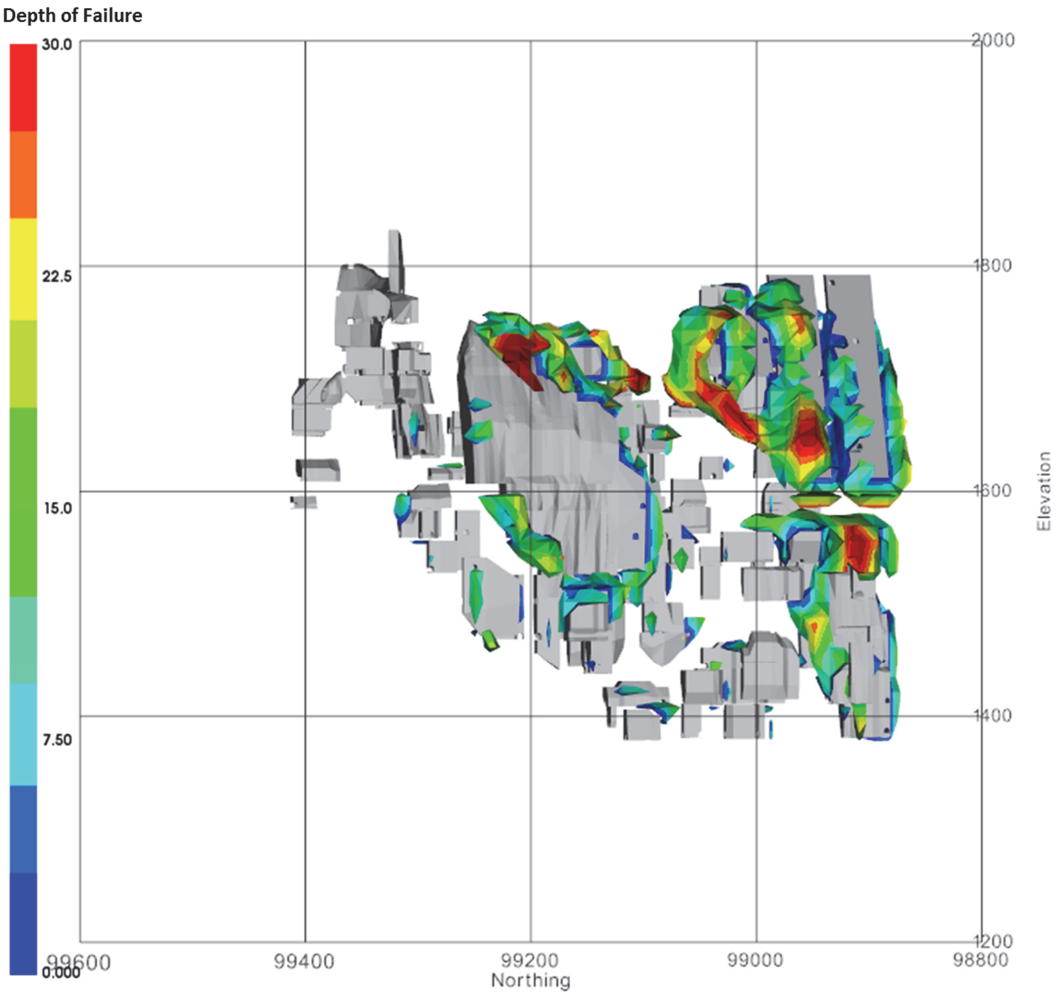

Figure 12 Modelled failure shapes and depths from the GMRi based on a zero excess stress iso-surface

The ability to highlight areas that have the potential for excessive overbreak is a valuable tool in the planning process. These areas can be flagged to increase pillar size or change designs to optimise the orebody and decrease operational risk.

5.5 Stoping extraction ratio

Generally, at pre-feasibility stage, certain assumptions are made for extraction ratio to prove that an orebody can be extracted profitably. These assumptions are often conservative and based on very little geotechnical input. The GMRi can be used to test the validity of such assumptions using empirically derived stope span strike lengths (Mathews et al. 1981) and pillar strike lengths (Lunder 1994). Practical adjustments are implemented for stope strike spans (maximum of 50 m) and pillar strike lengths (minimum of 5 m). With each grid point in the GMRi allocated a stope and pillar strike length, an extraction ratio was calculated within the GMRi using Equation 3:

$$\text{Extraction ratio \%} = \text{Stope strike length} / (\text{stope strike length} + \text{pillar strike length}) \quad (3)$$

The effectiveness of cable bolt support to increase stope spans was also evaluated using an empirically derived criteria for unsupported (Potvin 1988) and supported spans (Nickson 1992). The resulting spatially representative extraction ratios are displayed as a heat map on the stoping shapes to show the estimated extraction in Figure 13.

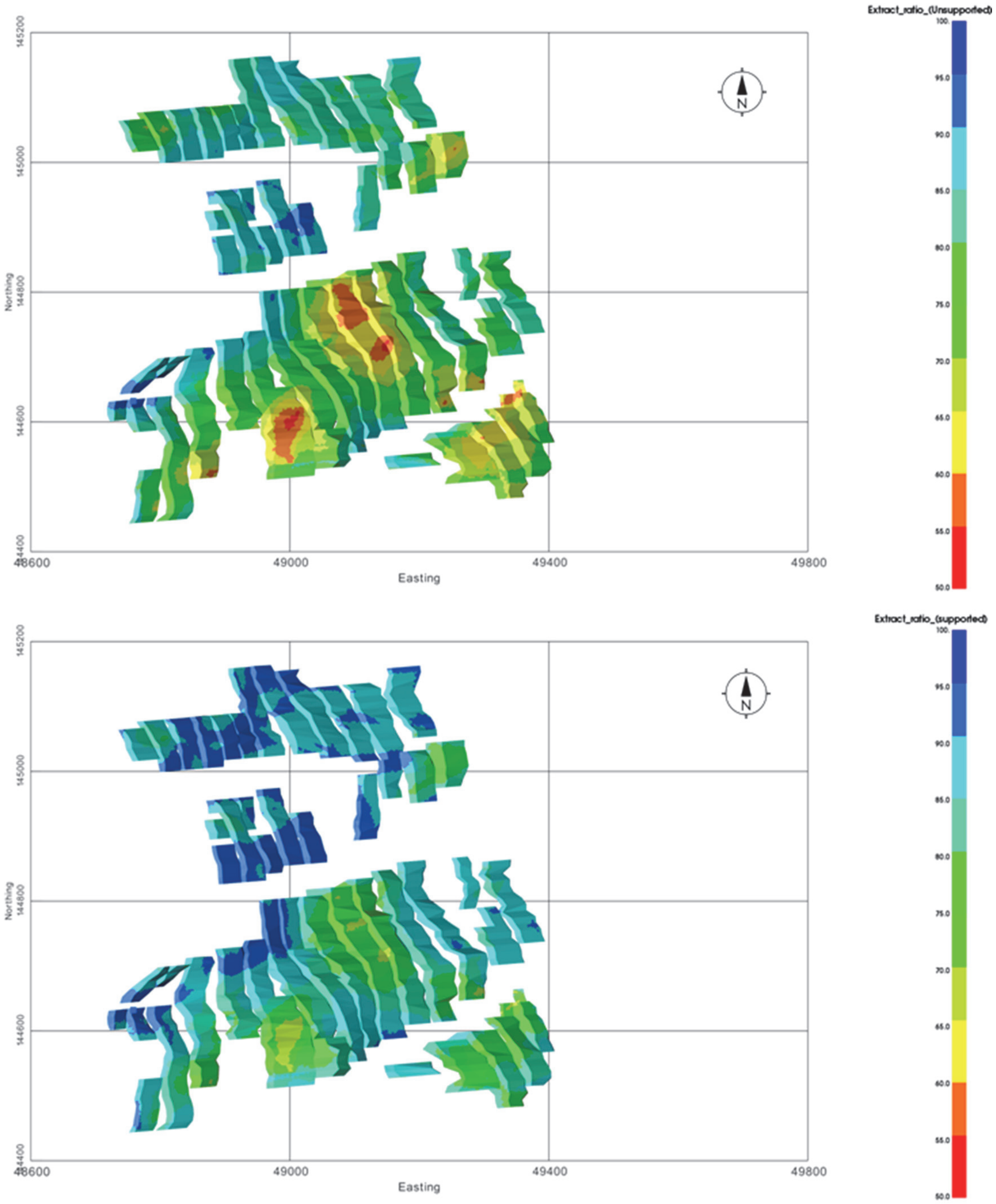

Figure 13 Extraction ratio (%) of planned stoping of the underground design with (below) and without (above) cable bolt support

The extraction ratio evaluation concluded that the assumptions of the pre-feasibility study were conservative and highlighted the opportunity for an increased extraction. The ability to visualise the areas of varying extraction highlights areas of opportunities and greater geotechnical risk. In the case above, areas of high grade and tonnage with lower extraction levels were identified to ensure optimal stope design, mining sequence and ground support design will be implemented to maximise value to the business.

6 Conclusion

Visualising data in 3D space is a powerful instrument for geotechnical analysis. The ability to build on this data by integrating design parameters and geotechnical calculations and relationships transforms this visualisation into an exceptional tool for geotechnical design and risk management. This forms the geotechnical model for rapid integration (GMRi), a prodigious and highly customisable tool that is easy to implement and utilise.

The GMRi concept has been successfully applied to evaluate the design of an underground operation at pre-feasibility stage and an established underground mine evaluating a mine-life extension area. By utilising the flexibility and ease of use of the GMRi, different parameters have been integrated based on the evaluation requirements and available data for each operation. This allows specific risk factors and opportunities to be highlighted, analysed and dealt with at an early stage in the planning process.

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