



Enhancing Slope Stability Analysis with Accurate Representation of Rock Bridges and Discontinuities

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Abstract. This paper introduces an advanced failure criterion methodology that integrates intact and fractured rock properties within geotechnical domains, using a 3D Mining Rock Mass Model derived from geotechnical logging data. The approach incorporates rock mass strength, fracture frequency, and joint roughness conditions (JRC) at varied joint orientations. Strength parameters are calibrated with laboratory data and available back analysis data and used in stability analyses.

The methodology provides a more precise slope stability assessment than conventional techniques by spatially mapping rock bridges and discontinuities. Case studies are presented to demonstrate the practical application in open-pit slope design.

Keywords: Slope Stability Analysis, Rock Bridge, Discontinuity, Mining Rock Mass Model.

1 Introduction

In geotechnical engineering, rock masses are composed of structural features such as bedding planes, joints, and foliation, collectively referred to as discontinuities or defects. Depending on the frequency of these discontinuities, rock masses are classified as either fractured or structured rock (with frequent discontinuities) or massive/intact rock (with minimal discontinuities).

Traditional slope stability assessments often focus on either the shear strength of the rock mass or failure along discontinuities, or both. However, these methods are typically incorporated into limit equilibrium or numerical models without precise identification of intact rock and discontinuity networks. As a result, conservative or optimistic assumptions are made to compensate for the uncertainty surrounding these features.

Accurate slope design requires understanding the complex interplay between intact and fractured rock. A rock mass composed entirely of discontinuities behaves differently from one that retains intact sections. Since most rock masses consist of both structured and intact portions, accurate spatial distribution and characterisation are essential for optimising pit slope design.

This paper introduces the outstanding results of using an advanced failure criterion methodology which integrates the effects of intact rock (rock bridges) and fractured rock (discontinuities) within each geotechnical domain derived from 3D Mining Rock Mass Model (MRMM).

2 Mining Rock Mass Model

A detailed geotechnical model of rock mass properties is a prerequisite for pit slope design. This model should incorporate the lithological units and structural features that control the geotechnical environment together with the geotechnical parameters required for analysis.

A comprehensive 3D Mining Rock Mass Model (MRMM) is constructed using detailed geotechnical logging data and mapping of existing pit [Seymour et al, 2007]. Geotechnical data includes rock mass strength, fracture frequency, Rock Quality Designation (RQD), and joint roughness conditions (JRC) at varied orientations (drill core logging ranges 0-30°, 30-60°, and 60-90°) [Dempers et al, 2010], capturing the anisotropic behaviour of the rock fabric. The MRMM comprises block models of each geotechnical parameter that are created using the raw logging/mapping data and estimated using the resource estimation routines available in geological software packages.

The block model estimation process is constrained by the likely controls on the geotechnical environment. The constraints are project specific and could include weathering profiles, lithology, foliation, bedding, major structural orientation etc. In addition, major faults and significant geotechnical features are also applied to constrain the block estimates. During the estimation process for each constraining unit, only the raw data for that unit is used.

The MRMM is interrogated in section and in plan to assess the variability of the input parameters and the project area is divided into geotechnical domains, an example of which is shown in **Fig. 1**.

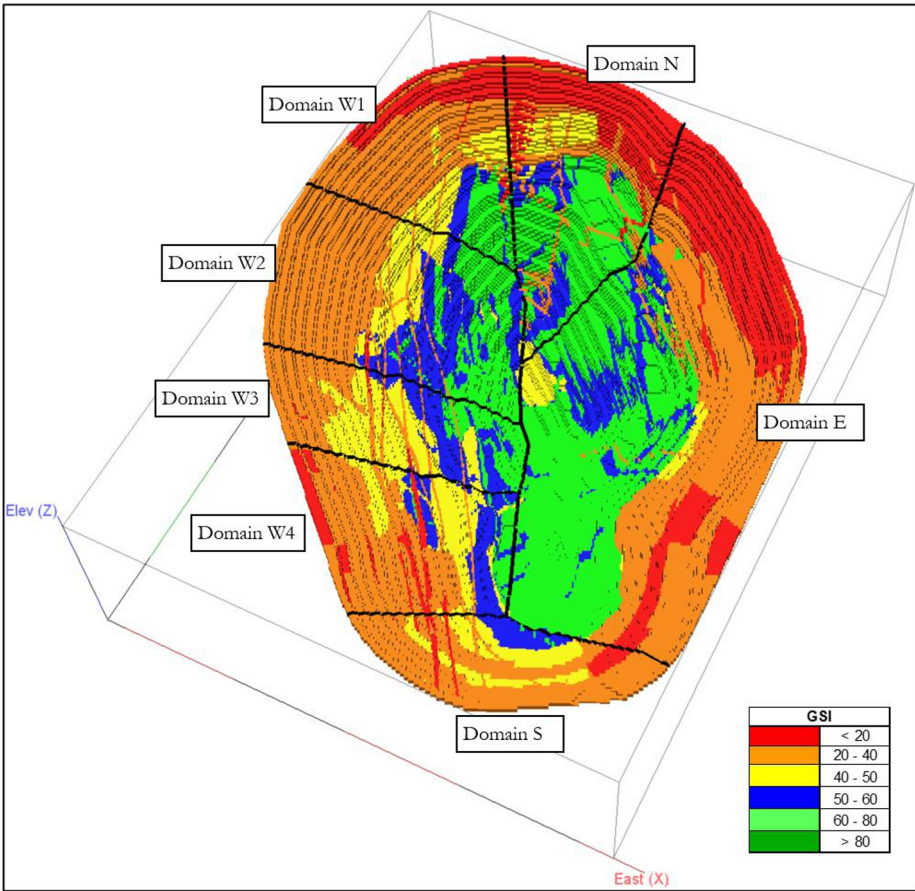


Fig. 1. A 3D view showing geotechnical domains derived from the MRMM GSI block model.

3 Rock Bridge Discontinuity (RBD) Methodology

The methodology applies strength parameters such as the Hoek-Brown and Barton failure criteria to reflect variability across rock mass domains. These parameters are calibrated with laboratory test data to ensure accurate representation of JRC and rock mass strength. Statistical analysis is performed on shear strength and rock bridge characteristics for each geotechnical domain, establishing a foundation for failure criteria models. These models serve as inputs for stability analyses conducted using Slide software, which accounts for the contributions of both rock bridges and discontinuities.

The proportion of rock bridge and discontinuity percentages for each unit within each geotechnical domain is determined from the RMR [Laubscher, 1990] fracture frequency rating (FFR). The FFR ranges from 0 to 40.

The percentage of rock bridge for each rock unit within each geotechnical domain is determined from the FFR block model in the MRMM with the maximum possible rock bridge set at 70% [Dempers et al, 2011].

Using the rock bridge percentage from the average FFR, the fracture frequency cut off rating is determined, above which the rock mass is assigned rock bridge with Hoek-Brown failure criteria. Material below the cut off represents discontinuities and is assigned Barton shear strength properties. The cut off is determined from the cumulative fracture frequency for each rock unit in each geotechnical domain obtained from the MRMM.

The MRMM is flagged, either rock bridge or discontinuity based on the FFR. It should be noted that the FFR cut off is applied to the competent rock units. Weathered materials, faults, structures and significant geotechnical features are explicitly modelled in the MRMM and generally exhibit behaviour associated with discontinuities and hence appropriate Mohr Coulomb parameters are applied during analysis. An example showing the various rock bridge and discontinuity categories is shown in **Fig. 2**.

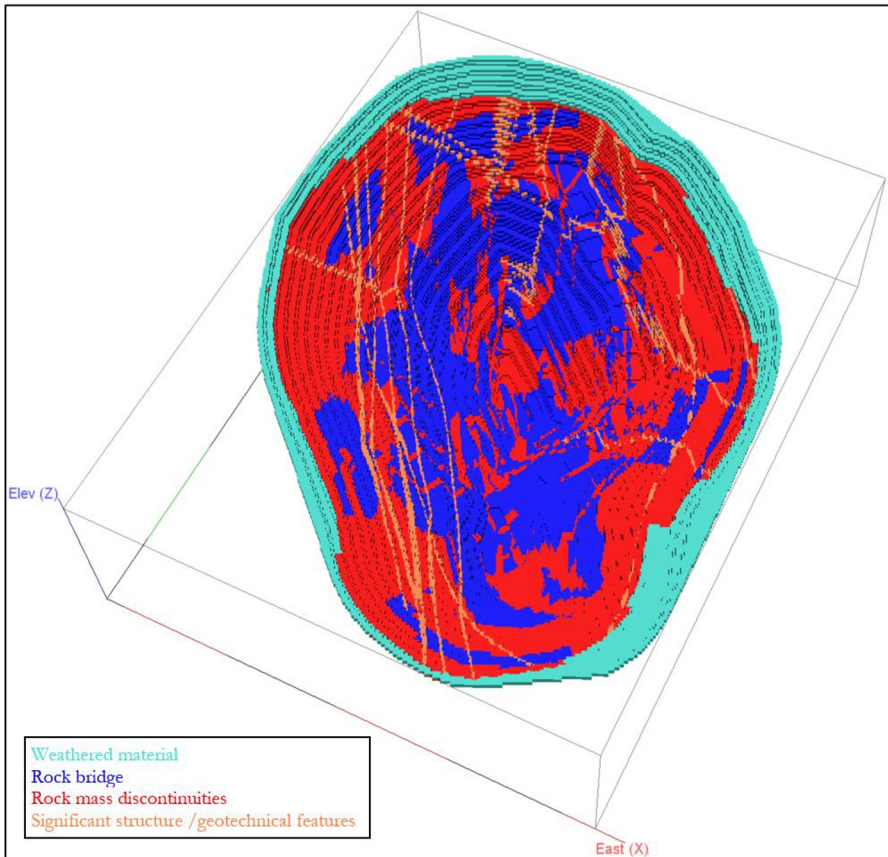


Fig. 2. A 3D view showing rock bridge, discontinuity, structure and weathered material distribution with the pit walls.

The relevant MRMM block models can be imported to RocScience Slide3 for pit slope stability analyses, examples of which are shown in **Fig. 3**.

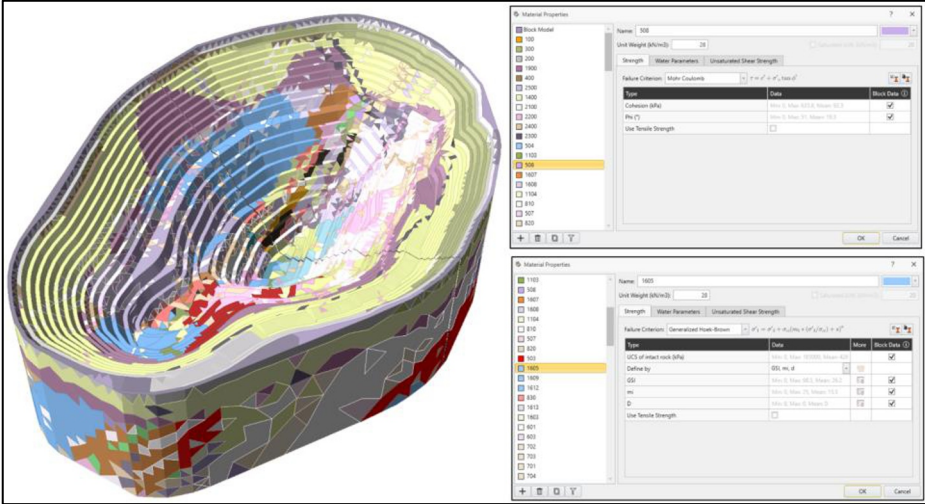


Fig. 3. MRMM exported to RocScience Slide3

4 Case Studies

4.1 Iron Ore Mine – Australia

The project comprises two weathered zones, 26 lithological units and 23 significant geotechnical structures. The MRMM was constructed, the existing pit design was assessed, and drone photogrammetry was carried out to create a 3D textured mesh [Nguyen et al, 2023] for evaluation of the mined pit. The modelled rock bridge, discontinuity and structure zones are compared with the actual conditions shown in **Fig. 4** and **Fig. 5**.

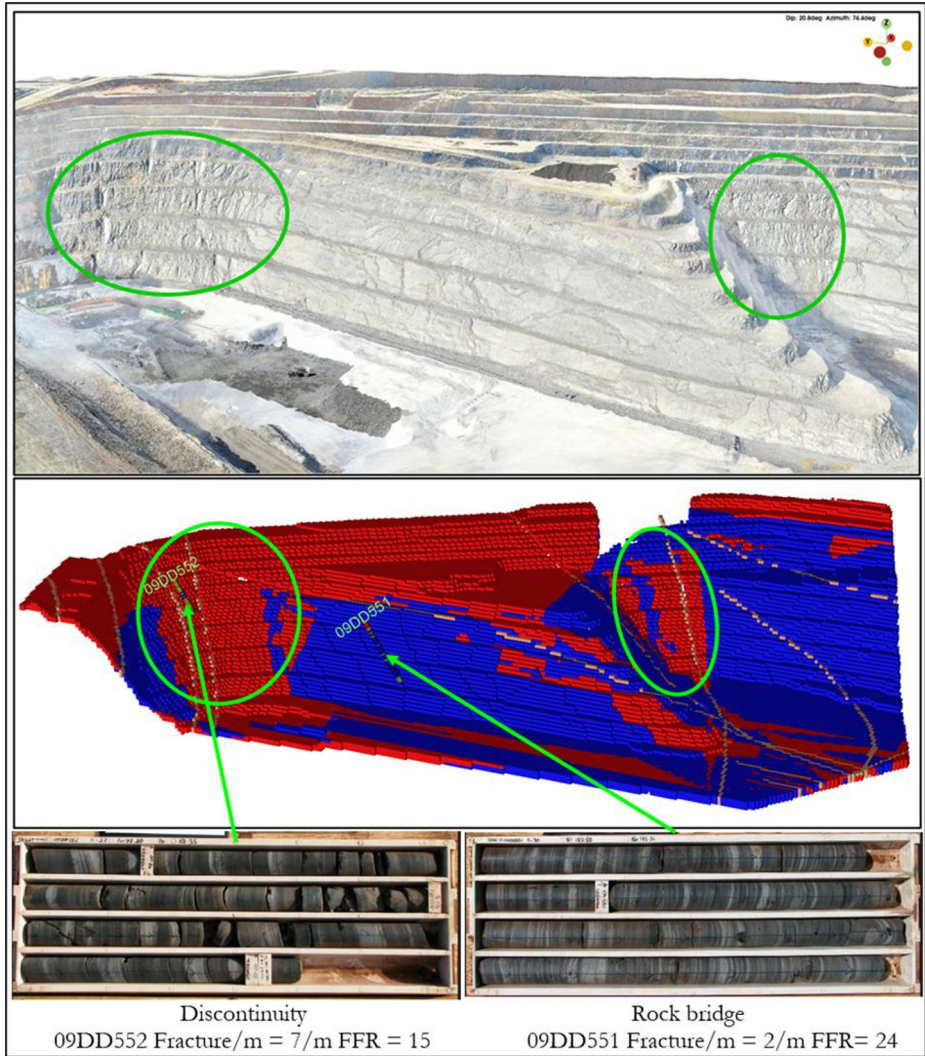


Fig. 4. East wall - Comparison mined pit walls vs MRMM rock bridge (blue), discontinuity (red) and geotechnical feature (orange) domains

Core photos from the pit wall intersections show rock bridge and discontinuities defined by the FFR. There are two discontinuity zones in the pit walls (highlighted) which are evident in the MRMM model. These zones are a result of a change in orientation of the pit wall, exposing the discontinuities in the rock fabric. The geotechnical features which are modelled independently can also be seen in **Fig. 4**.

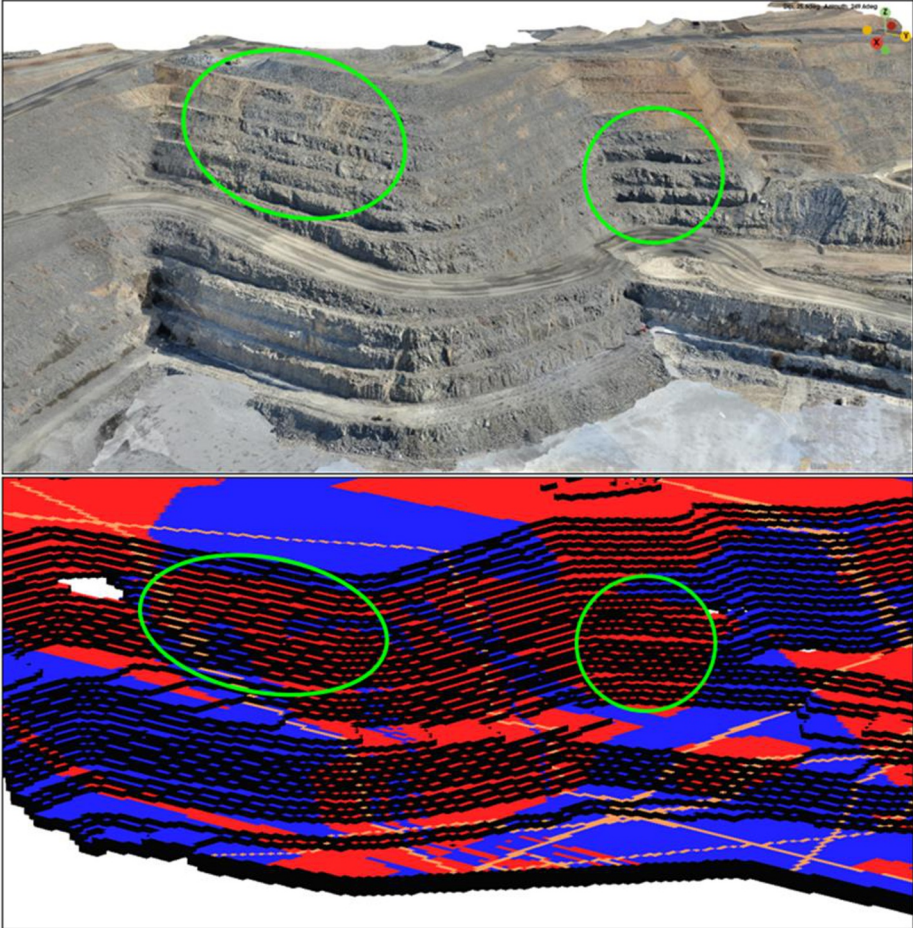


Fig. 5. West wall - Comparison mined pit walls vs MRMM rock bridge (blue), discontinuity (red) and geotechnical features (orange) domains

Zones of rock bridge and discontinuity in the pit walls are represented in the MRMM, examples of which are highlighted in **Fig. 5**.

4.2 Gold Mine – Africa

The project comprised two weathering units and seven lithological units which were used to describe the geotechnical environment. In addition to the lithological and weathering units, ten significant geotechnical features were modelled. 3D wireframes of these units were used to constrain the MRMM block model estimates.

The pit slope design was undertaken using the RBD methodology and the pit was subsequently mined. The MRMM was compared with the actual conditions encountered in the pit walls in particular the modelled rock bridge and discontinuity zones.

Representative sections of the pit walls and the MRMM rock bridge domains are shown in **Fig. 6**. Rock bridge zones highlighted in the pit wall photographs are shown in the corresponding MRMM screen picture.

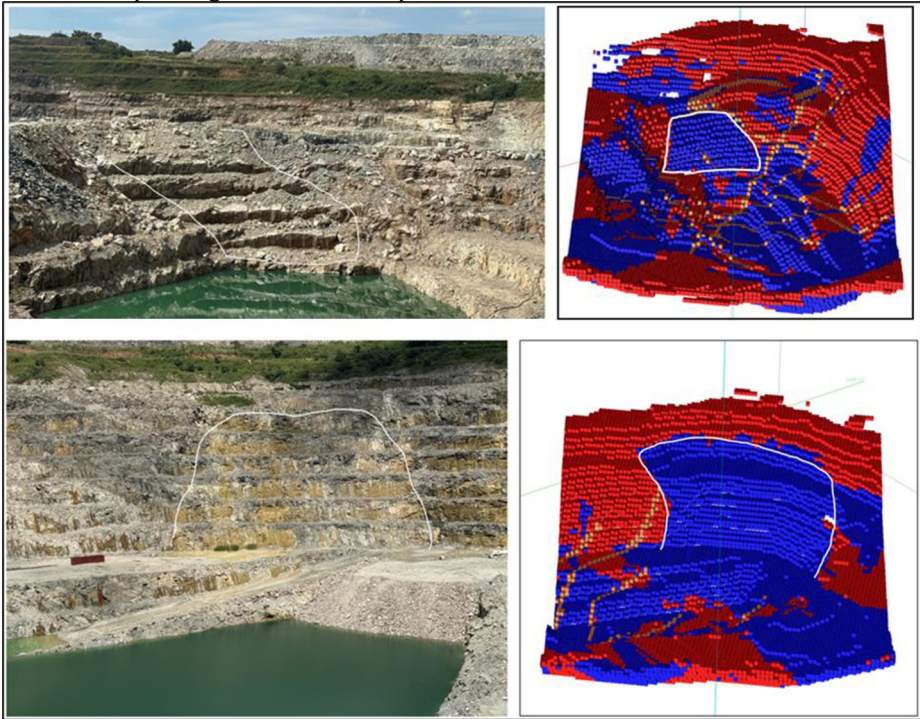


Fig. 6. Comparison mined pit walls vs MRMM rock bridge (blue), discontinuity (red) and geotechnical feature (orange) domains

The ground truth calibration is good. Within the rock mass forming the pit walls, zones comprising rock bridge and discontinuities are represented in the MRMM.

The methodology allowed appropriate parameters to be applied at the design stage that represented the actual conditions when the pit was mined. The pit slope performance was good and whilst there was some small-scale batter crest loss due to blasting and oversteepening of batter angles there were no major pit wall stability issues.

4.3 Gold Mine – Australia

The project comprised six weathering units and eight lithological units. In addition, 17 significant geotechnical structures were identified and modelled in 3D in the MRMM.

The pit slope design was undertaken using the RBD methodology and mining commenced in the pit. The modelled rock bridge, discontinuity, weathering and structure zones are actively compared and monitored as mining is progressing. Drone photogrammetry surveys were carried out for assessment of the actual conditions and com-

pared to the rock bridge / discontinuity model. Examples of the comparison are shown in **Fig. 7** and **Fig. 8**.

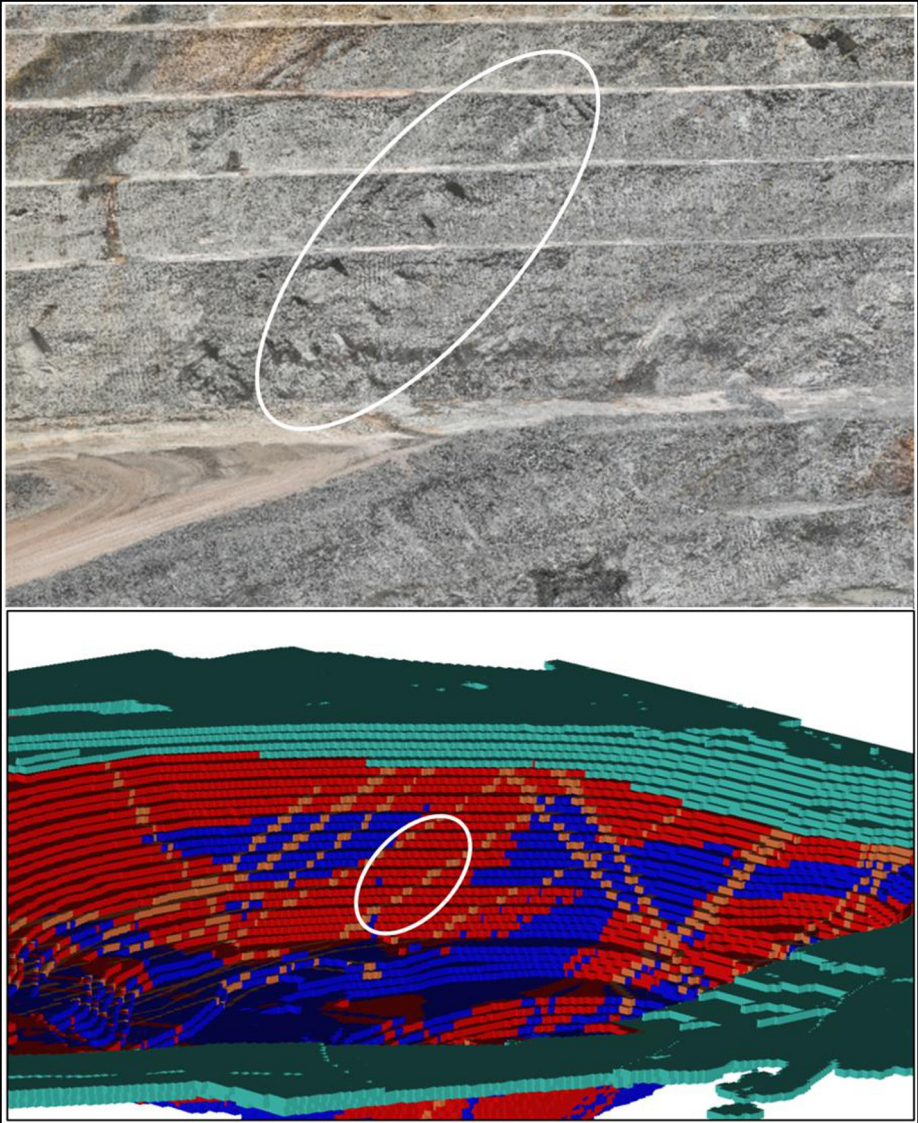


Fig. 7. South wall - Comparison mined pit walls vs MRMM rock bridge (blue), discontinuity (red) and geotechnical feature (orange) domains

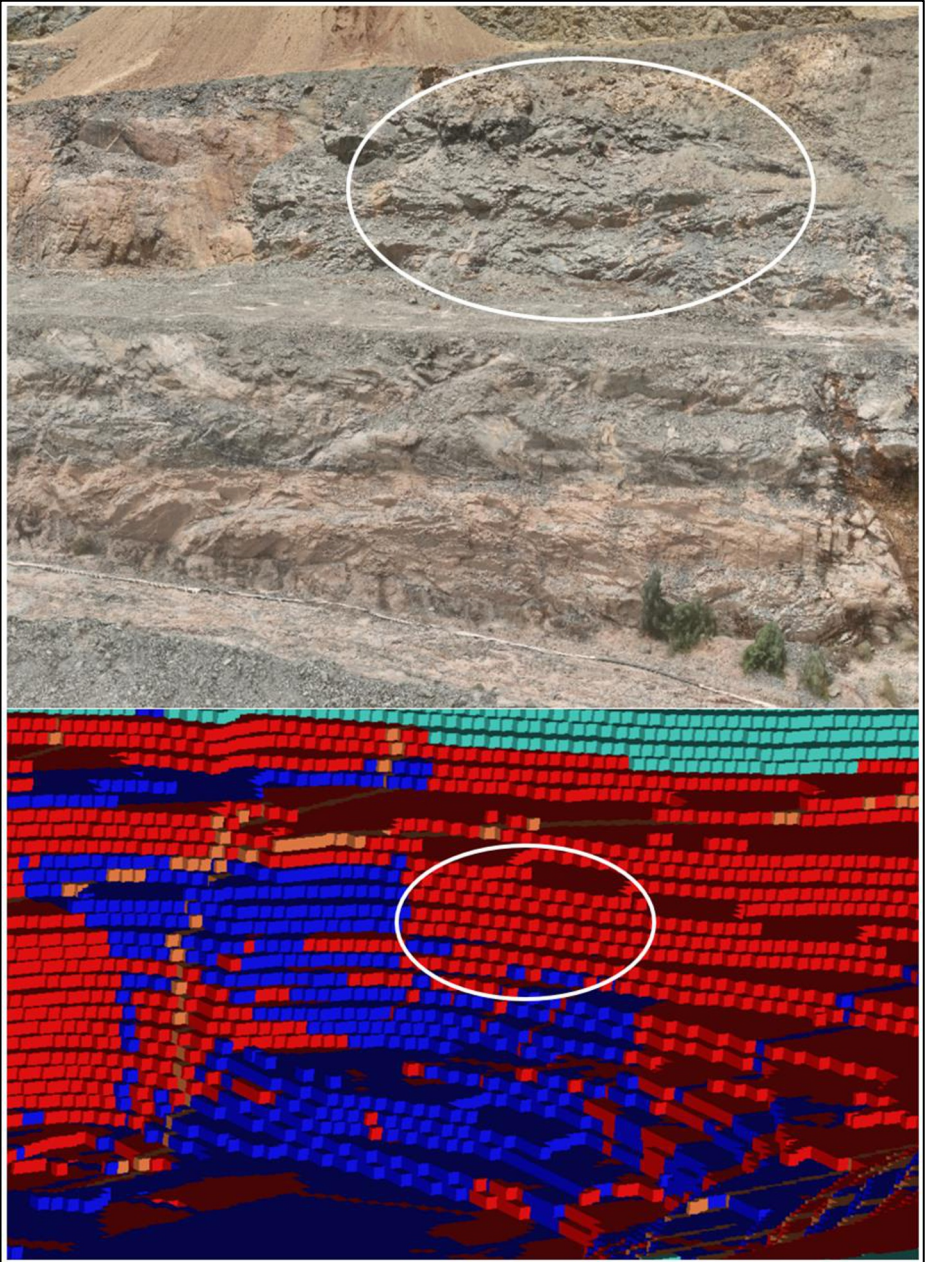


Fig. 8. East wall showing the MRMM flagged with rock bridge (blue), discontinuity (red) and geotechnical feature (orange)

5 Conclusions

Ground truthing demonstrates the Rock Bridge Discontinuity (RBD) design approach allows for a high level of accuracy and confidence of pit wall design angles applied to mine design. By incorporating rock bridges into stability assessments, this methodology provides a more realistic representation of rock mass behaviour.

The RBD design methodology optimises accurate and precise 3D spatial distribution of the rock mass condition and characterisation enabling informed decision-making before and during mining.

The methodology is based on measured rock mass parameters. These parameters are used to create a 3D block model that represents the variability of the rock across the project. The appropriate parameters can then be accounted for in the pit slope design process and can be used by geotechnical practitioners with access to 3D modelling tools and slope design software.

The MRMM is accurately constructed using lithological units and structural features that control the geotechnical environment together with the geotechnical parameters required for analysis. Major structures and significant geotechnical features are incorporated in the MRMM so that the extent and orientation of these features can be accounted for during pit slope analysis and design.

Detailed geotechnical logging data records parameters for varied orientations (0-30°, 30-60°, and 60-90° in drill core logging) that capture the anisotropic behaviour of the rock fabric. This allows classification of rock bridge and discontinuity within the rock mass and appropriate failure criterion can be applied during pit slope analysis.

Case studies demonstrate that the methodology was successfully applied in designing pit slopes, proving its accuracy and reliability. The approach effectively predicts actual conditions, ensuring more precise and dependable slope stability assessments.

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