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The benefits of undertaking robust structural mapping for the slope design, management and excavation processes

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Abstract

An accurate understanding of the role of discontinuities, in defining the physical properties of the rock mass, is required to assist in the excavation of stable slopes. For open cut mining operations, the continual sampling of the rock mass, through structural mapping of bench and highwall faces, can provide an abundance of high quality discontinuity data. In this paper, the authors will discuss some of the complicating issues associated with structural mapping, including scanner data acquisition, analysis and interpretation that geotechnical engineers regularly encounter. They will also discuss the benefits of mitigating these issues and undertaking such an analysis for improvement of the slope design, management and excavation processes.

1 Introduction

Thorough and reliable characterisation of the rock mass is required for an accurate understanding of the stability of an excavated or natural slope. For structurally controlled failure mechanisms, characterisation of the rock mass discontinuities associated with the failure modes requires measurement of their surface properties, geometry and the spatial distribution. The discontinuities in a rock mass typically consist of faults, joints, bedding, and other planes of weaknesses. Therefore, the numbers of discontinuities being considered in an analysis may be large depending on the model size, type of analysis being conducted and serviceability criteria of the slope. The use of statistical techniques to infer the presence of ’unseen’ discontinuities based on those that have been sampled through borehole logging or field mapping has been described extensively (Baecher et al. 1978; Dershowitz & Einstein 1988) and methods to represent them explicitly as discrete fracture networks (DFN) for computational analysis are becoming more common (Jing 2003).

The connectivity of the DFN is directly related to global properties of the rock mass such as its permeability and fragmentation. The latter is of particular interest for slope stability analysis of heavily jointed and blocky rock masses. The formation of blocks or polyhedra (the terms are used interchangeably throughout this paper) as a result of the connectivity of the DFN can be modelled. Accurate block representation in computer modelling of the rock mass improves the reliability of subsequent geotechnical analyses and, of particular interest for this paper, slope stability analysis. This increased reliability in analysis is of value for mine operators as it supports improved design and therefore performance of slopes and more informed decision-making in operational matters such as response to changing ground control conditions.

Figure 1 shows the relationship between major mining processes, some higher order rock mass properties, and the underlying rock mass fracture properties. The dependence is ‘many-to-one’ and it can be seen that properties such as persistence are extremely important to quantify for multiple processes (shown in red/darker shading). High fracture persistence, when combined with high fracture connectivity, strongly influences the in situ fragmentation of the rock mass. Fragmentation influences the performance of slope stability, excavation and drill and blast operations, as well as comminution processes.

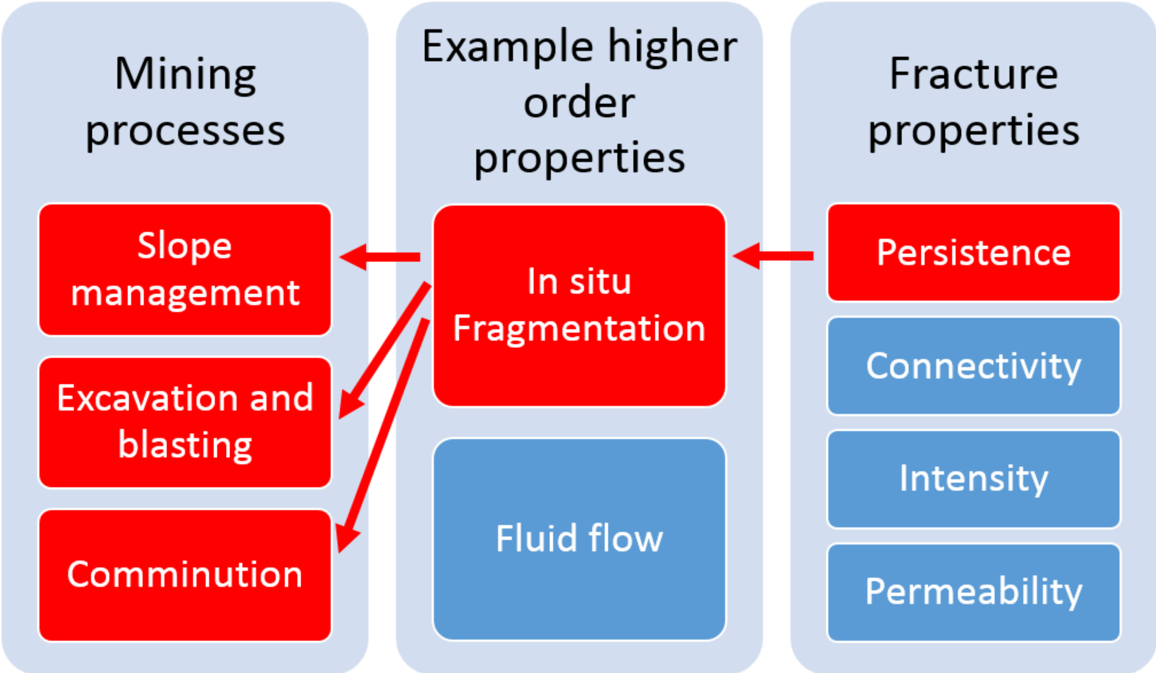


Figure 1 Relationship of mining processes to phenomena which are heavily controlled by fracture properties — for clarity, only a single example of a particular dependency is shown in red/darker shading

This paper presents a discussion of considerations and techniques to apply to structural mapping. The techniques are available to the industry through third party hardware and software, and some are based on CSIRO research and development, which is now commercialised or available to industry sponsors of the original Large Open Pit Slope Stability Project (LOP 1) and the Australian Coal Association Research Program (ACARP). Section 2 of this paper will discuss some of the issues associated with characterising rock mass structure accurately in the field. Section 3 will then present examples of improved geotechnical analysis capabilities for management of design and operation of slopes in civil and mining operations that can be realised through accurate rock mass structure characterisation.

2 Structural mapping

2.1 Scanning technologies

Characterisation of rock mass structure in modern mining and slope excavation operations can benefit from a suite of modern technologies. For borehole logging, optical and acoustic televiewers can be used to accurately measure the fracture frequency of fracture populations that are oriented favourably given the borehole orientation. Of course, the issue of sampling bias is present with all sampling methods and borehole logging is particularly susceptible. These issues have been well described by many prominent practitioners (e.g. Baczynski 2000), and for a recent review, please refer to Fowler (2013).

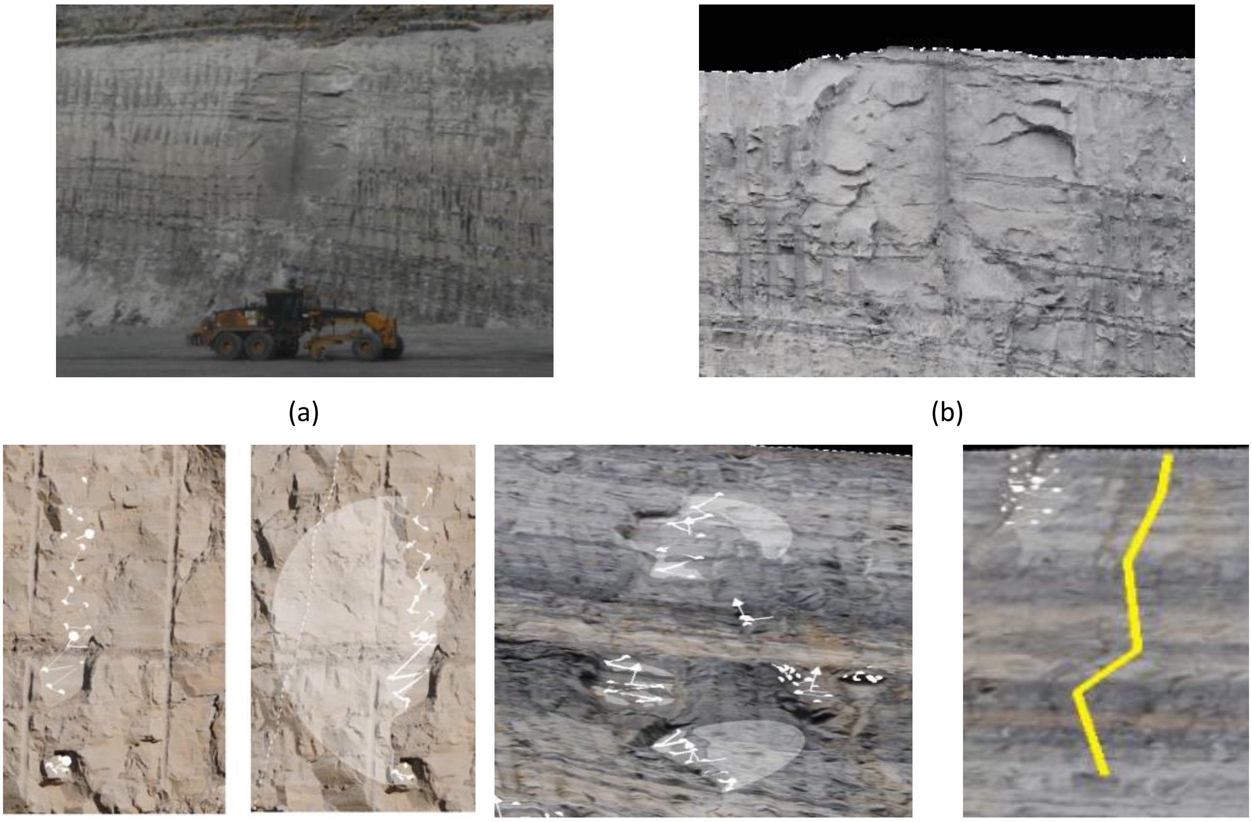
Exposure mapping has also benefitted from advances in technology and now photogrammetric and laser scanning systems, both terrestrial and aerial, are readily available. Although less biased than borehole logging, window sampling also suffers from sampling biases. Some noteworthy issues are discussed below.

The use of automated structure mapping algorithms is also becoming more widespread. Several software packages now provide users with the ability to import topographic data, define some thresholds based on structure orientation and area, and automatically map quasi-planar structures. There is a danger to using such approaches blindly because such algorithms tend to overestimate the numbers of structures but under-estimate their persistence. This over-segmentation problem is still a major concern and can produce extremely misleading results for the unwary practitioner (Krahenbuhl et al. 2014).

2.2 Biases in digital acquisition of structural data

A number of sampling biases, other than the commonly understood ones (size, orientation, truncation and censoring, see Priest 1993 for details), exist as a result of the finite sensing abilities of digital and non-digital sensing alike. Orientation bias requires special mention, as although the use of window mapping avoids the severe sampling bias associated with linear sampling techniques (Park & West 2002), the linear geometries of benches and coal highwalls make orientation bias an issue. Characterisation of frequency of occurrence of structures sub-parallel to the wall is extremely difficult. Traditional methods of correcting for this bias (Terzaghi 1965) are only useful if sufficient numbers of structures from the set have been observed to derive accurate statistical parameters for the discontinuity set. Alternatively, if no quantification of frequency is possible, a conservative approach should be adopted where the structure should be incorporated in a scenario analysis. Orientation bias is a serious issue and limits the predictive capabilities of highwall mapping when only a single, linearly oriented strip is available.

Digital sensing merely provides access to a more rapid acquisition of larger structural data sets and therefore greater opportunity for some of these biases to take effect. Some of these biases have been analysed using now commercialised CSIRO developed 3D photogrammetry and structural analysis software and are summarised in Figure 2. Excavator scaling of walls can mask small scale discontinuities. Multiple mapping of a single, larger scale structure can occur if visual continuity across the structure is not obvious. This will lead to the underestimation of persistence and experienced practitioners should pay close attention to mitigating this. Curvature, or waviness in structures, is ever present but rarely captured in digital data. Once again, attempts to work around limitations in planar representation of rock mass defects can introduce biases. Use of digital images as opposed to naked eye surveys performed in the field, can also be problematic. If a structure set is oriented unfavourably relative to the ambient lighting and/or camera/laser position, it will be difficult to resolve and may even be absent from the spatial data. No simple correction method is possible and the wall may need to be reimaged with alternate field work geometry and/or adequate lighting conditions.



(a) (b)

(c) (d) (e)

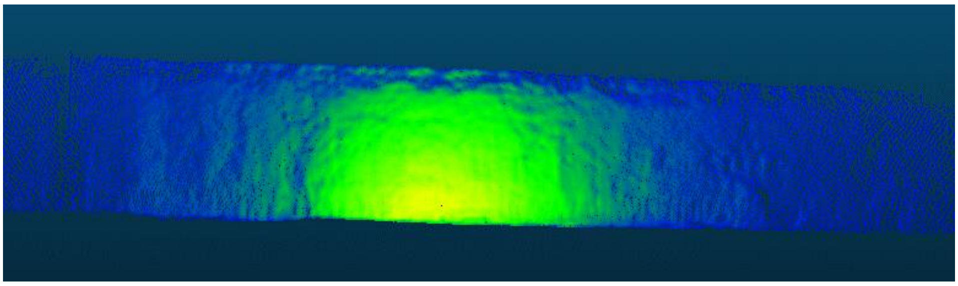
Figure 2 Less commonly discussed sampling biases of relevance to structural mapping

Depending on the requirements of the analysis, pre-split and blast-induced fractures may or may not be of interest. In any case, distinguishing between the blast damage and in situ joints is usually important and relies heavily on the ability of the practitioner to recognise characteristics associated with blast damage such as plumose structures, fracture orientations parallel to highwall and proximity to blast holes.

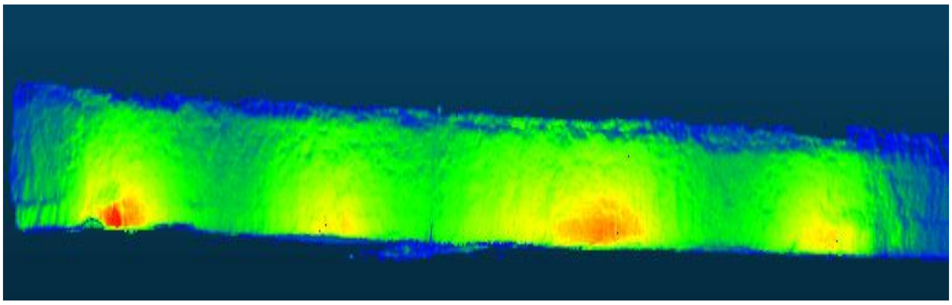
Excavation artefacts (Figure 2(a)) such as bucket teeth marks and drillhole half-barrels can mask minor structures in the rock mass. For practitioners using automated structure mapping algorithms, these artefacts can be especially problematic. Blast damage (Figure 2(b)) can be obvious as shown or more subtle. The ability for the practitioner, or automated structure detection algorithm, to discern may be limited and this may impact down-stream geotechnical analyses. Under-estimation of persistence can occur due to the manual or automated mapping strategies failing to recognise the common source of defects mapped across larger scales (Figure 2(c)). Methods to correct this over-segmentation by joining structures can mitigate this problem. Curved discontinuities can be mapped multiple times or using a single, planar approximation. Both methods misrepresent the true persistence and variability of the defects (Figure 2(d)). Insufficient resolution of the point cloud or mesh for mapping distant structures, or insufficient contrast in the digital image used to render the three-dimensional data for discerning faint structures or traces, will lead to under-sampling of these structures (Figure 2(e)).

2.3 Optimal use of scanning technology

Previous authors have discussed the issues of sampling bias associated with view oriented scanner locations (Lato et al. 2010). The use of multiple scanning positions and integration of resulting data sets has long been recommended to mitigate the effects of occlusion of unfavourably oriented structures and uneven point density/spatial precision (Figure 3). However, it is apparent that with the rapid increase in use of photogrammetry and laser scanning systems, many practitioners are using such scans for geotechnical characterisation of excavations without full appreciation of the problem.



(a)



(b)

Figure 3 (a) Single scan and (b) multiple scans, yielding uneven point density across the scanned face. Red (or darker regions) at centre of each scan zone indicate higher point densities

Recently, Allemand et al. (2016) analysed the significance of sensor location, bench face orientation and structure orientation on the sampling process. A schematic of the analysis is shown in Figure 4. A scanner of given scanning resolution is located in front of a dipping wall containing discontinuities with specified location, size and orientation.

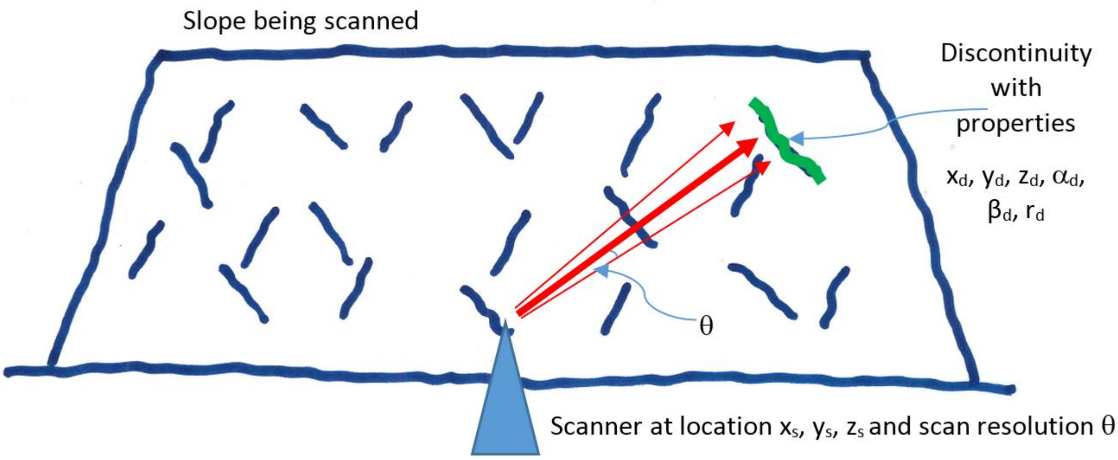


Figure 4 Schematic of the analysis of the impact of sensor location and resolution. A discontinuity with location, orientation and size properties is also shown

An analysis of the influence of the finite scanner resolution on the achieved point cloud on each of these discontinuities has been performed for a typical scenario experienced in Australian open cut coal mine highwalls. A highwall dipping at 90 degrees and containing a conjugate set of discontinuities has been simulated. Figure 5 shows the results for the case where the sensor is located 100 m from the bench. For this analysis, discontinuities are assumed to be 2 m in size and dipping at 90 degrees. It is acknowledged that for some applications, such as analysis of larger scale failures of open pit mine slopes, a study focussed on larger structures may be warranted. The dip direction of the discontinuities is varied from 180 degrees (i.e. parallel to the bench) through to 270 degrees (90 degrees to the bench). The colour map shows the number of points on the discontinuity surface as discontinuity dip direction and location, read scanner bearing to discontinuity, is varied. A high scan resolution of 0.025 degrees has been assumed.

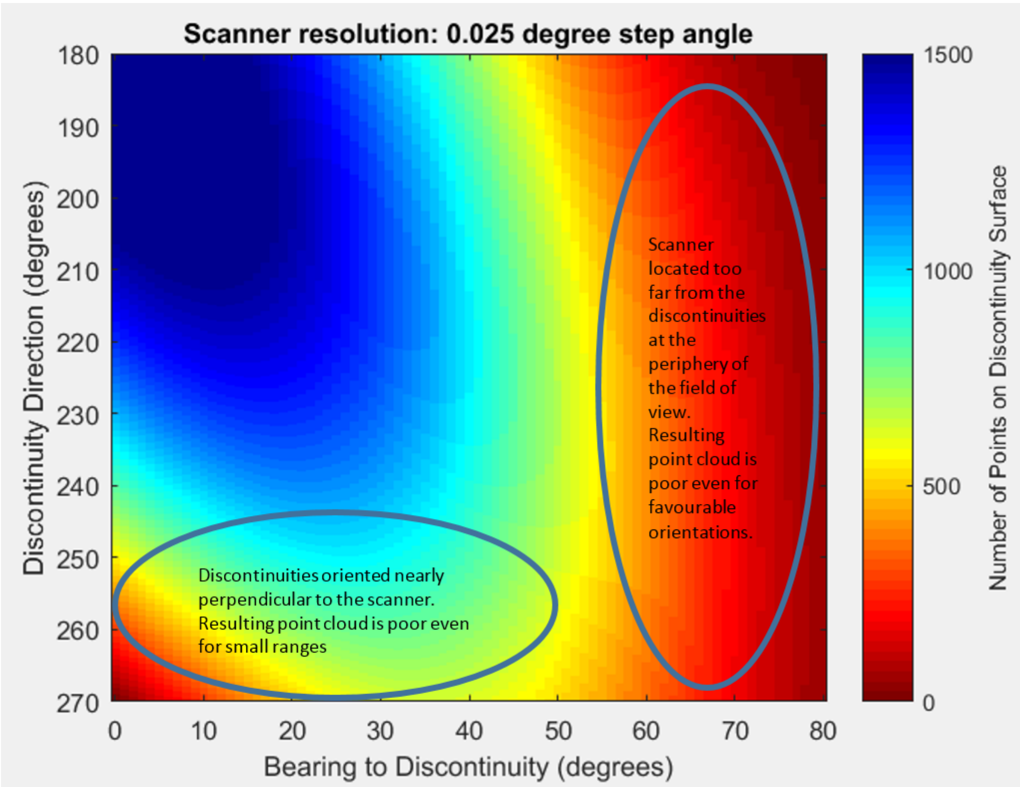


Figure 5 Comparison of achieved point clouds on discontinuities as a function of bearing and discontinuity directions. Assumes scanner is located 100 m away from the wall and the discontinuities are 2 m in size and dipping vertically

Note that even for the high scan resolution, the number of points on the scanned discontinuity can become very low for discontinuities oriented unfavourably or located towards the periphery of the scanner field of view. The impact of such poor sampling can be inaccurate estimation of discontinuity orientation or even undetected discontinuities.

Although scanner manufacturers advise their clients that the highest scan resolutions should be used for geotechnical analyses, the time penalty associated with this scan mode can make use of lower scan resolutions tempting. As a cautionary tale, Figure 6 shows multiple plots for various scan resolutions achievable by laser scanners ranging from a high resolution scan with step angles of 0.025° down to low resolution of 0.2°. All other parameters in the analysis have been unchanged as for the analysis shown in Figure 5. One can notice the dramatic decrease in the number of points that will be scanned on a discontinuity face due to the decrease in scan resolution.

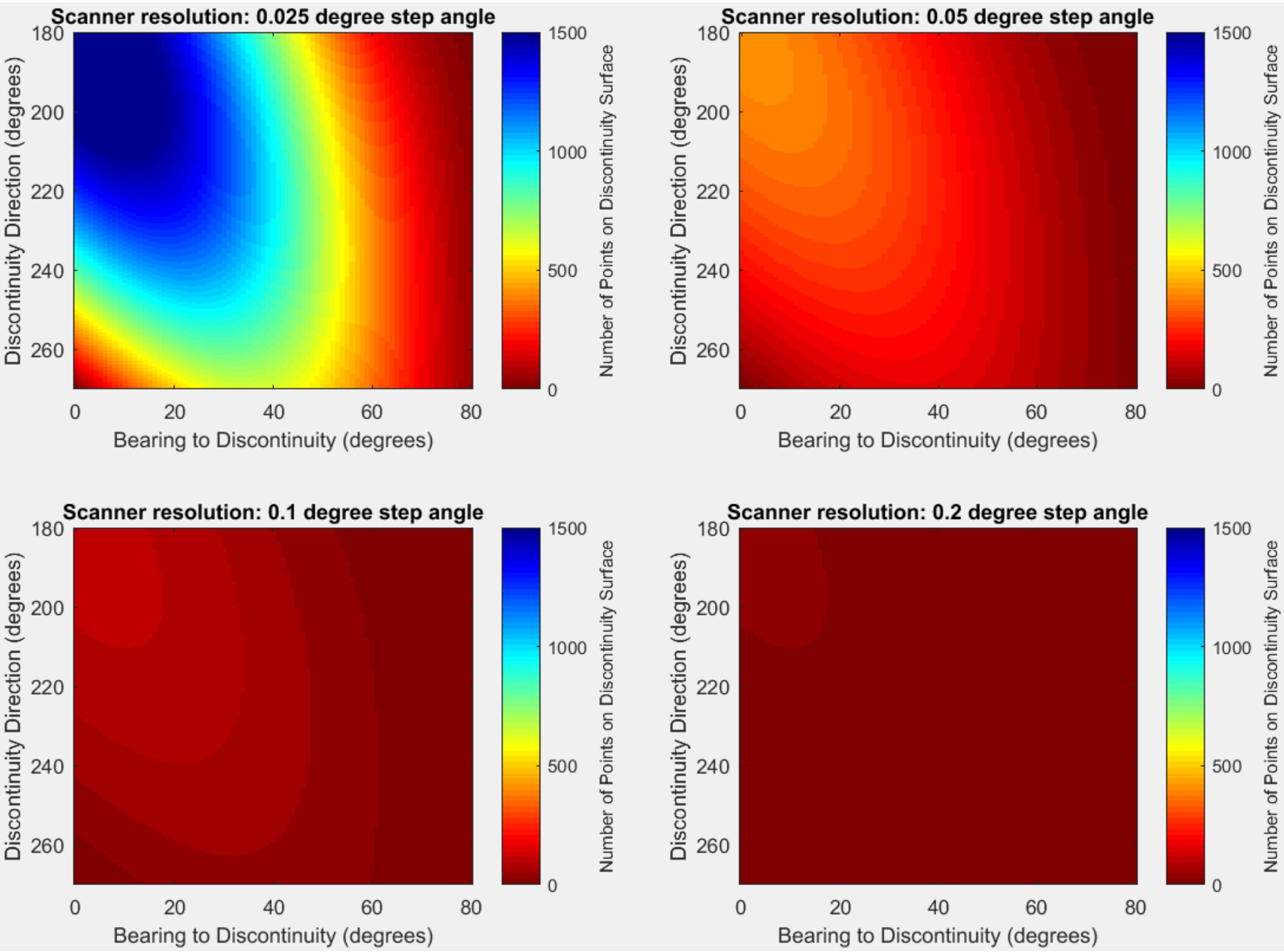


Figure 6 Comparison of varying scan resolutions (0.025, 0.05, 0.1 and 0.2°). Assumes scanner is located 100 m away from the wall and the discontinuities are 2 m in size and dipping vertically

2.4 Data interpretation

The interpretation of the mapped discontinuities is subject to the practitioner's knowledge of the structural geology of the setting and the conceptualisation of the discontinuities. The use of restoration based structural geological modelling has been shown to be beneficial for assessment of validity of conceptual models of fracture networks (Watkins et al. 2014). Further, the representation of the discontinuity geometry in analytical or numerical modelling necessitates simplifications, e.g. planar discs, limitations on numbers of structures represented etc.

All conceptualisations, simplifications and limitations should be noted by the practitioner so that the down-stream geotechnical analysis is interpreted within this context and appropriate reliability is attributed to the analysis. Figure 7 shows a process by which this interpretation is formally recognised in structural analysis. This accounting then informs the reporting of geotechnical analyses to the operations and management personnel. For example, consider a scenario where a slope stability analysis is undertaken for a proposed excavation. It is based on numerical modelling with many simplifications used to represent the rock mass heterogeneity, fracture network properties and failure mechanism physics. The output of the report is a Probability of Failure assessment of various slope geometries based on a multi-realisation stochastic modelling methodology. For other engineering disciplines, e.g. manufacturing, data interpretation may be less troublesome and such metrics could be reported in isolation from the modelling assumptions. For geosciences and slope engineering in particular, this luxury does not exist and terms like Factor of Safety and Probability of Failure should be accompanied by the specifications of the particular analysis. Lorig et al. (2009) provides some information on the various slope design methods available to the practitioner and their strengths and weaknesses.

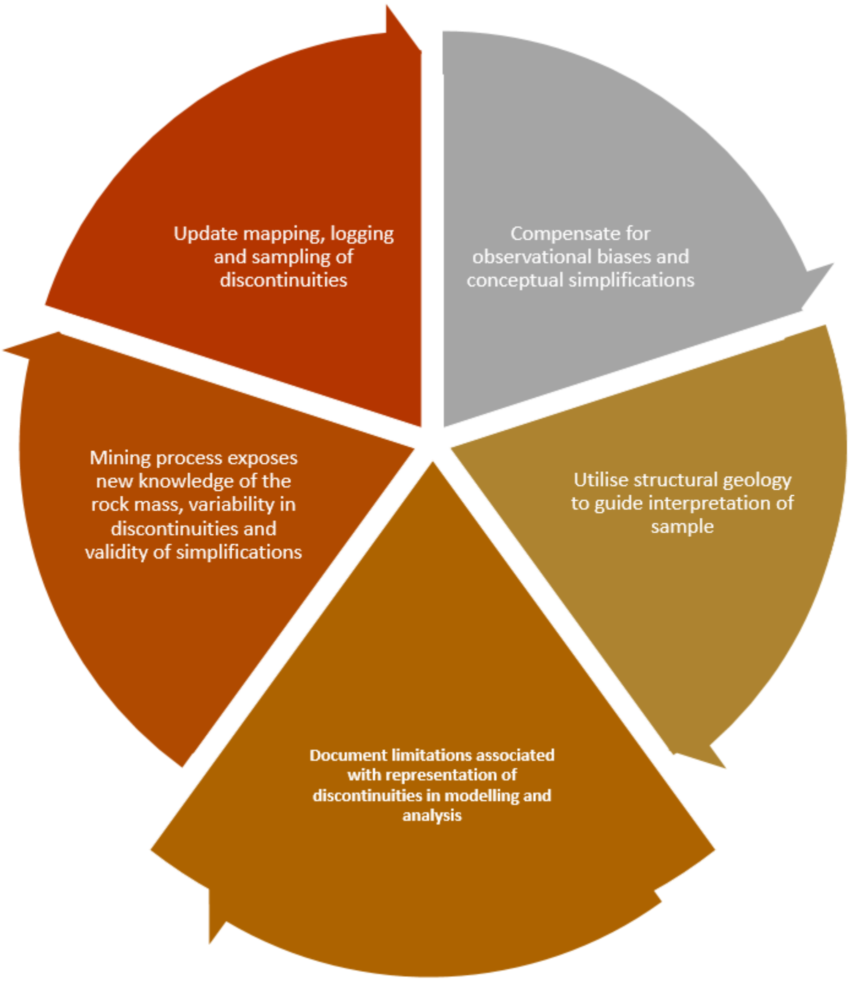


Figure 7 The structural analysis process evolves with additional understanding of the properties and variability of the rock mass. Documentation of the conceptual model and modelling simplifications for representation of discontinuities is vital for correct interpretation of reliability and context of down-stream analyses

3 Geotechnical analyses

Section 2 described some of the issues associated with structural mapping and representation of discontinuities in analyses and provided recommendations for deriving a quality geo-structural database through robust mapping processes. Such a database forms a critical input for many slope stability related geotechnical analyses, both traditional and modern. In the following section, the authors will describe two recently developed geotechnical analysis methods that benefit from this process.

3.1 Excavation analysis

A recently developed excavation analysis method developed by the CSIRO and detailed in Elmouttie et al. (2016) is now described. The method utilises software developed by CSIRO and available to industry sponsors of the Large Open Pit Slope Stability Project. Analysis of the optimal slope geometry given the constraints imposed by the structural characteristics of the rock mass is fundamental to slope design. A stability isoplethogram is a means of interrogating the stability characteristics of the internal rock mass for proposed excavation geometries. This concept was described by Windsor and Thompson (1996) who developed the technique as a method of determining the likelihood of unstable block formation in surface and underground excavations. This two-dimensional contour diagram displays the contour lines (also known as isopleths) associated with the rock mass feature being investigated as a function of potential excavation plane orientation being examined. The horizontal and vertical axes normally represent the dip directions and dips, respectively, of planes representative of potential excavation surfaces.

The process of generating an isoplethogram, for the assessment of current or proposed excavations, will now be summarised. The first step consists of a site characterisation capturing the structural geology of the setting. As discussed previously, definition of the rock mass discontinuities included in the structural model can then occur. Next, the uncertainty associated with the sampling methods used is included appropriately in the model. Major structures, such as faults and bedding, and minor structures mapped on exposures are typically represented as deterministic structures in the structural model. The population of un-sampled minor structures are represented stochastically. Careful consideration of the structural domains is required in this process. Multiple stochastic realisations of the structural model can then be generated. For each realisation of the structural model, the multiple excavation planes being considered can be assessed and a stability analysis against each plane is undertaken. In this paper, a rigid block, limit equilibrium stability analysis applied to the polyhedra detected by the polyhedral modeller, is used. However, this same process is applicable to continuum or coupled continuum-discontinuum modelling approaches. Statistics on the stability of each excavation plane, such as volume of failed material, are accumulated. Finally, isoplethograms can be generated displaying the results for each excavation plane and the statistic of interest.

This excavation analysis algorithm has been applied to a section of an open cut mine located in Queensland, Australia. The geology of the open pit site consists of four major lithological units of a general dip of approximately 65° to the west, i.e. tubular. Structural data for the open pit was acquired using the photogrammetry technique.

Figure 8 shows the portion of the open cut mine that was examined using the excavation isoplethogram analysis algorithm. The figure shows the lower benches of the northeast area of the pit.

Figure 8 Site used for the analysis

In order to perform an excavation isoplethogram analysis to analyse the performance of this bench geometry, a volume of interest was defined around this model assuming a theoretical single bench excavation with face angle of 90° and 40 m height. The excavation isoplethogram analysis was conducted using this deterministic DFN and the polyhedral model is shown in Figure 9.

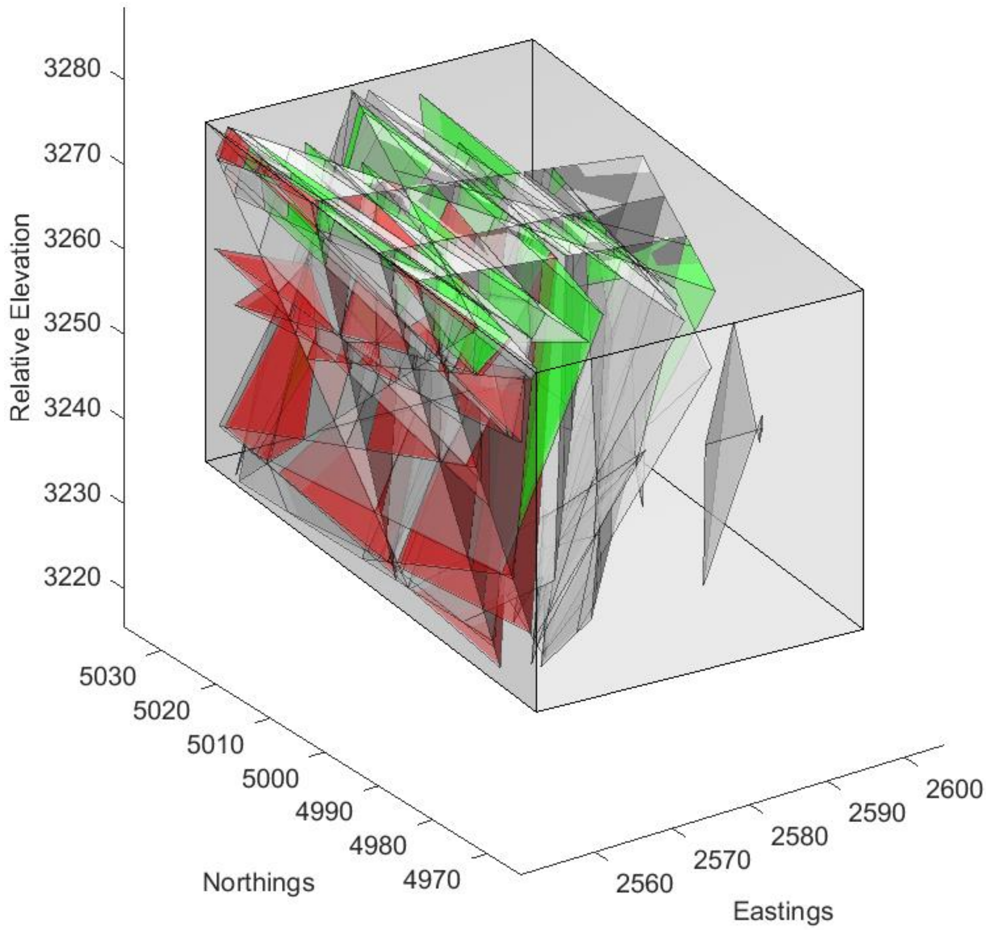


Figure 9 Polyhedral model excluding polyhedra in contact with boundary surface

The isoplethogram plot in Figure 10 shows a comparison of the volume of removable blocks associated with each excavation plane tested in the analysis. The bright regions, labelled hotspots A and B, indicate excavation planes with dips ranging from 50 to 75° as being particularly prone to failure. The actual bench orientation (275/70°) corresponds to a ‘cool spot’ in the image. The hot spots are approximately located at dips of 60° and dip directions of 220 and 320°.

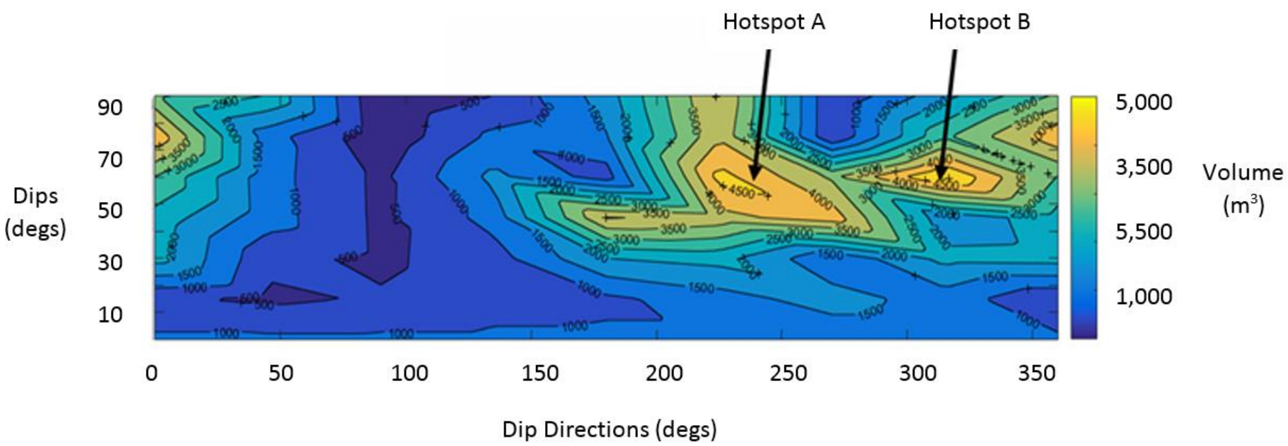


Figure 10 Failed volume excavation isoplethogram (in m^3) for the data shown in Figure 9

Analyses using the DFN approach expose uncertainties in the rock mass characterisation process present in all modelling approaches. Interpretation of results should therefore be made in this context. In particular, the influence of sampling biases requires consideration, particularly when the presence of a structure set that is sub-parallel to the wall is suspected as being a dominant factor in observed failure mechanisms (as is the case here). The observation in Figure 10 that the actual bench orientation corresponds to a local minimum, in terms of failure volume, must therefore be interpreted with this bias in mind.

It is important to once again highlight the role of this type of analysis within the context of the full slope design process. The excavation analysis method presented is based on a rigid block stability analysis. The progressive failure analysis described in this paper applies this stability analysis iteratively as each unstable polyhedra is removed from the analysis. This approach does not account for fracture propagation or rock mass failure. Therefore, if field observations confirm the likelihood that composite failure mechanisms will constrain the slope design parameters, the excavation isoplethogram analysis must be performed in conjunction with a slope design process capable of capturing these more complex failures. Reliance on out-sourced resources in expertise and modelling capability may be required, particularly if numerical modelling of composite type failures is desired. This is because, in the author's opinion, the calibration, simulation and validation of such numerical models is still a significant undertaking. If such resources are not available, empirical methods may be required (Lorig et al. 2009). In all cases, clear statements of the capabilities and limitations of the modelling should be included in the reporting.

The prior analysis was based on a deterministic DFN. There are many uncertainties associated with rock mass characterisation, and parameter variance associated with properties of the structures (persistence, orientation) can be significant. To investigate this, a stochastic variance (standard deviation of 5°) was applied to the orientations of these structures whilst retaining the structure locations (as determined from their centroids) and assumption of persistence constant. This approach has been termed a quasi-stochastic analysis (Elmouttie & Poropat 2012) because it uses a combination of deterministic and stochastic variables to define the individual structures in the DFN. A Monte Carlo simulation was performed comprising 100 DFN realisations. The excavation isoplethogram, describing failed volume averaged over 100 simulations, is shown in Figure 11. Although similar to Figure 10, there are some notable differences.

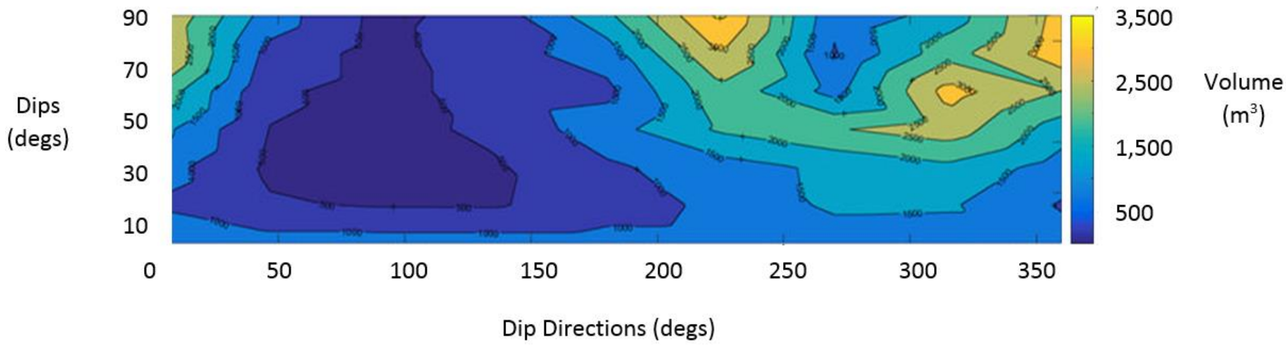


Figure 11 Failed volume excavation isoplethogram (in m³) for the region of interest — quasi stochastic analysis

Hotspot A identified at (220/60°) is no longer a local maximum although the one at (320/60°) remains. The peak value in the plot is now 3,500 m³, around 1,000 m³ less than that predicted using the deterministic analysis. The proposed algorithm using the stochastic approach therefore has significant potential for determining the trustworthiness associated with interpretation of individual features in the analysis.

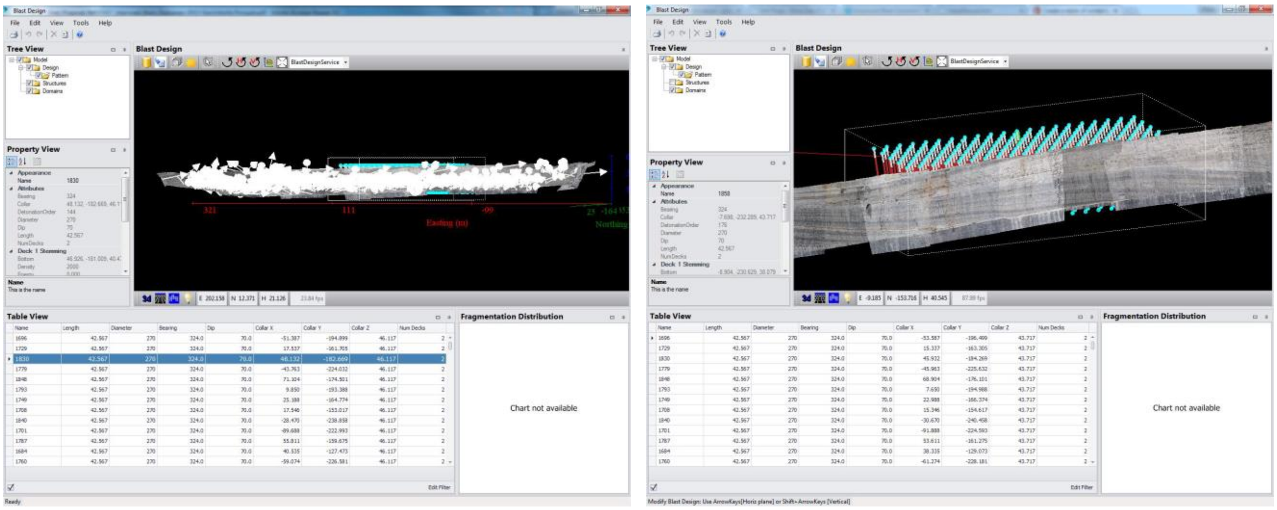
3.2 Use of structural mapping for improved blasting of slopes

Accounting for rock mass structure in the drill and blast operations of mining and civil engineered slopes is crucial for efficient use of resources and achieving satisfactory final slopes. In recent work undertaken by the CSIRO in collaboration with the Sustainable Minerals Institute (SMI) and detailed in Dean et al. (2015), a method was defined to assist both the geotechnical and drill and blast engineers achieve such outcomes.

The CSIRO was tasked with developing the Blast Analysis Tool (Dean et al. 2015) which would serve to integrate the SMI expertise in blast energy estimation and post blast fragmentation analysis with CSIRO structural modelling capabilities. The blast energy estimation is based on the Julius Kruttschnitt Mineral Research Centre (JKMRC) 4D energy distribution model, (time-weighted), to calculate the energy throughout the blast zone (Kleine 1988; Onederra & Chitombo 2007).

Blast fragmentation modelling approaches range from empirical to numerical. The empirically based Kuz-Ram model (Cunningham 1983) is probably the most well-known. A blast fragmentation prediction algorithm that accounts for heterogeneity in rock mass structure, and more accurately predicts fines, has been used in this paper. This algorithm was developed by the JKMRC and utilises an energy based comminution approach (Sarma 1994). The blast energy at each point is provided by the aforementioned 4D distribution model. Breakage functions for specific rock types have been derived based on laboratory testing conducted by the JKMRC. Finally, an estimation of the in situ block size distribution (calculated using the polyhedral modelling approach described in Section 3.1) forms the input to the algorithm.

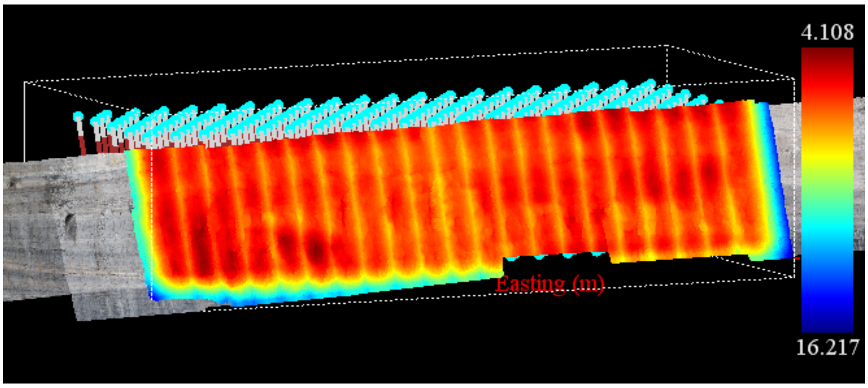
The method involves generating a blast design, topographic and structural data using third party packages. The practitioner can then import these data into what is referred to as the Blast Analysis Tool (Dean et al. 2015). A screenshot of this tool is shown in Figure 12.



(a) (b)

Figure 12 Blast analysis tool (Dean et al. 2015) interface showing (a) blast design, topographic and structural data; and, (b) close-up view of topography and blast design

For the assessment of blast design efficiency and identification of potential hazards such as face-bursts, a multi-criteria approach has been adopted. The tool allows the practitioner to take into account several criteria, including face burden, predicted energy intensity (a function of face burden), structural connectivity, fracture intensity and an index to classify the overall properties of the geotechnical domain. Several analyses are shown in Figure 13.



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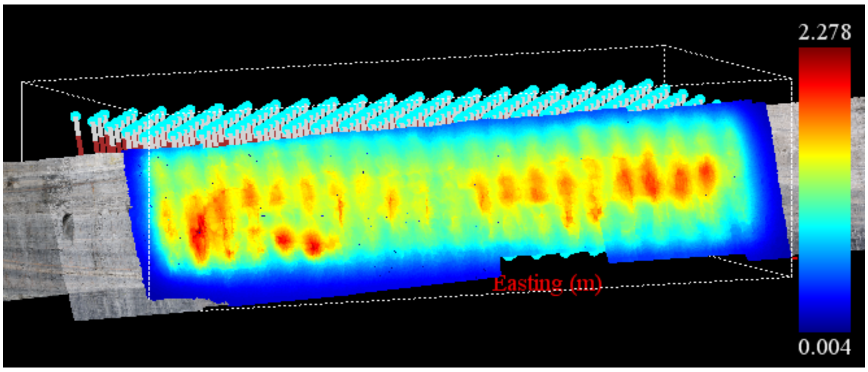

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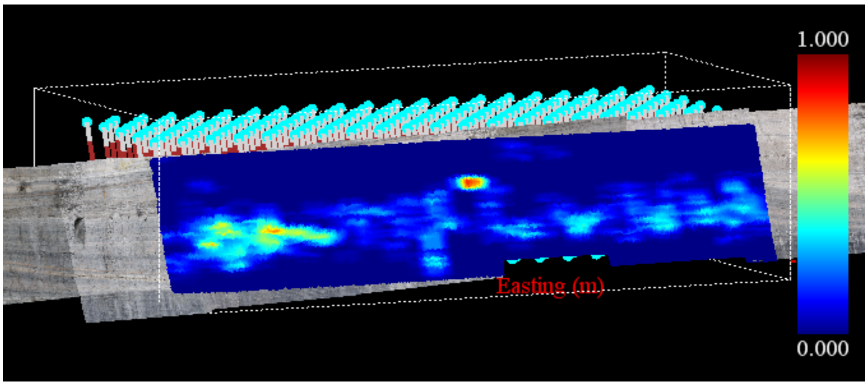

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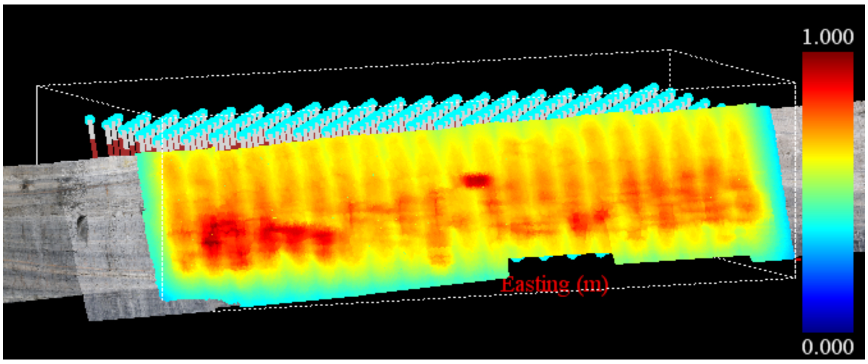

(d)

Figure 13 Example screenshots showing the results of the individual criteria of: (a) face burden; (b) energy intensity; (c) fracture intensity; and, (d) multi-criteria analysis. Red indicates higher values

The face burden tool (Figure 13(a)) enables the user to examine the compatibility of the blast design with the actual topography of the highwall. It uses the location of the front row of the design in relation to the surveyed topography of the highwall. The energy intensity calculation (Figure 13(b)) uses the blast design layout and the topography of the highwall and calculates the blast energy at each point on the highwall using the elemental charge approach developed at the SMI. The fracture intensity (total fracture length per area) can also be included in this analysis (Figure 13(c)). The structural connectivity examines the connection pathways between rock mass defects identified in the structural data and the blast design. Finally, in the multi-criteria analysis, each criteria can be assigned a different weighting to take account of prior knowledge or experience of the practitioner for the particular highwall or geological setting (Figure 13(d)).

Regions identified in this map with either high or low values can be interpreted in the context of the analysis as representing inefficient blast performance or having potential for face-burst.

To provide an improved estimate of blast induced fragmentation, a prediction of the in situ size distribution can be generated by the tool using the structural mappings. This estimation involves calculation of both the volumetric joint count and, if sufficient data is available, the polyhedral volume estimation. The tool will then calculate a prediction of the post-blast fragmentation using this in situ estimate. This calculation can be performed on a domain-by-domain basis and, thus, different rock types and rock qualities can be accounted for. An example fragmentation curve is shown in Figure 14.

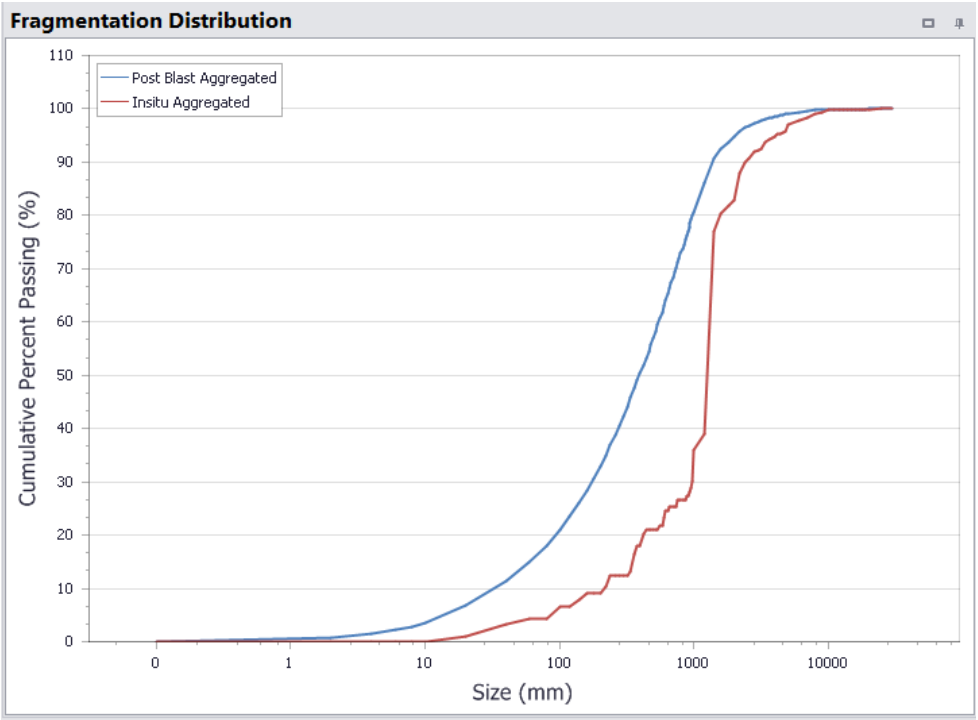

Figure 14 Pre- and post-blast fragmentation curves estimated for the example data

4 Conclusion

In this paper, we have outlined the value of undertaking a robust structural mapping program for the design and management of slopes. Methods to undertake structural mapping with particular attention to digital scanning technologies have been described. Sources of bias were discussed along with mitigation strategies. Finally, the benefits of these methods for two particular types of geotechnical analyses pertinent to slope stability, namely excavation analysis and drill and blast design, have been detailed.

The techniques used in this paper are currently available to the industry through a number of commercialised or industry sponsored technologies. What prevents their more widespread use is likely a combination of lack of awareness and resources. With improvements in both technology, as well as intuitiveness and usability, the adoption of these quantitative and powerful slope design methods will increase.

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