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Preliminary identification of persistent or pervasive discontinuities from borehole data

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Abstract

Open pit slope designs are often controlled by persistent or pervasive discontinuities in a rock mass. Whether a discontinuity will be important for inter-ramp and overall scale assessments is difficult to ascertain, especially for development projects without exposed outcrops. Such assessments often rely on observations from individual boreholes grouped on stereonets without consideration of how discontinuities might link between boreholes.

This paper provides a preliminary methodology to identify persistent or pervasive discontinuity sets from boreholes with televiewer or oriented core data. If at least three boreholes are drilled proximal to each other, a plane can be fit through discontinuities from each borehole. The pole vector from each measured discontinuity can be compared with each other, and to the fitted plane, to connect similarly oriented discontinuities across the boreholes. The angular distance between the mean of the measured pole vectors and the fit plane pole vector can be filtered to remove poorly matched discontinuities, leaving a set of discontinuities that are either persistent across the boreholes or sufficiently pervasive that non-persistent planes link up (e.g. bedding planes).

The methodology can be extended to any georeferenced discontinuity orientation data to connect borehole and mapping measurements. This may be useful to connect mapped discontinuities across benches, identify through-going structures and improve persistence estimates.

The approach is useful for set ranking, interrogation of structural domain boundaries, and preliminary justifications for some degree of rock bridging. Discontinuity orientations that do not intersect at least three boreholes cannot be assessed with this methodology, especially if the boreholes are widely spaced, short, or have large differences in collar elevations.

This paper illustrates the methods and potential applications of this approach using a demonstrated example from three boreholes through a pit wall with photogrammetry data.

Keywords: *persistence, set ranking, borehole data, censoring bias*

1 Introduction

Geotechnical open pit slope designs are often controlled by persistent or pervasive discontinuities in a rock mass. Whether a discontinuity will be important for inter-ramp and overall scale assessments is difficult to ascertain, especially for development projects without exposed outcrops. Such assessments often rely on observations from individual boreholes grouped on stereonets without consideration of how discontinuities might link between boreholes. Shallow dipping discontinuities are particularly limiting and often create bi-planar shaped failure mechanisms in kinematic and anisotropic stability analyses. These analyses conservatively assume the discontinuity set is either sufficiently pervasive to occur throughout the slope, or persistent enough to create the basal surface.

Discontinuity orientation measurements in proximal boreholes or outcrop mapping can be extended in space to intersect other measurements, and filters can be applied to compare to the intersected measurement. Each measurement can be systematically compared to other measurements in neighbouring boreholes or outcrops to identify discontinuities that are either sufficiently persistent to be present in multiple data sources, or sufficiently pervasive that non-persistent discontinuities link up across data sources.

Methodologies to interpret the importance of a discontinuity set, by either ranking it or estimating its persistence and spacing, have been developed and implemented in open pit designs and other contexts. This paper extends these concepts beyond individual boreholes or subjective discontinuity matching, allowing the practitioner a data-supported justification for persistence estimates and set ranking.

2 Background

The significance of a discontinuity on the geotechnical stability of an excavation has been described by various authors (e.g. Cruden 1977; Priest 1993; Brown 2003; Tuckey et al. 2012; Mathis, 2020) using its persistence, type, infilling, weathering, state of degradation, and proximity to other similar discontinuities. Identifying significant or through-going discontinuities and assessing their potential to be daylighted by the excavation is critical to inter-ramp scale open pit slope design, however, it remains a very difficult interpretation.

The persistence and spacing of a discontinuity set determines the size of potential blocks that could form during excavation. Borehole investigations are often the most direct evidence of rock mass characteristics available for open pit greenfield sites, and are plagued by the biases they introduce. Discontinuities in individual boreholes are a point measurement that are difficult to link to other point measurements. If outcrops are available, direct persistence estimates can be made with the understanding that the data will be biased by truncation at bench crests/toes or censoring of the discontinuity. Priest (1993) and Sturzenegger (2010) showed that persistence estimates are 'censored' when only a portion of the discontinuity is visible on the rock face, and the majority is hidden in the rock mass or already excavated. This is a natural consequence of having a two-dimensional plane available in most outcrops and may also occur when the mapper is not aware they are recording multiple small exposures of the same discontinuity. Brueckman (2016) defined censoring bias as "the difficulty in measuring the total length of discontinuity trace lengths that extend beyond the visible exposure and one or both ends of the trace is not visible". Censoring bias is most pronounced in borehole data where persistence cannot be observed directly, despite boreholes often being the only direct sampling or observation of the rock mass in question.

Inter-ramp and overall scale assessments require an understanding of both persistent and pervasive discontinuities. Discontinuity persistence tends to follow an inverse frequency relationship, where regional-scale discontinuities occur less frequently than small-scale joints (Priest 1993). Tuckey et al. (2012) showed that, while the importance of persistent discontinuities is important, non-persistent discontinuities occur more frequently than persistent discontinuities and are also likely to create kinematic failure modes. Fabric that is sufficiently pervasive to link together discontinuous discontinuities can be an inter-ramp control that is indistinguishable in an individual borehole, and difficult to identify when mapping an outcrop.

Attempts to include discontinuity persistence in slope stability analyses and constitutive models are numerous and are summarised in Tuckey et al. (2012). These approaches rely on applying analytical tools and engineering judgement to field data that conceptually project the discontinuity plane through the rock mass that is not visible in outcrop. Observations of discontinuity slickensides, infill, weathering, occurrence in swarms, and damage in the intervening rock mass have proved helpful in systematically ranking set importance from individual boreholes (Mathis 2020), but do not directly address censoring bias.

Brueckman (2016) compared televiewer measurements from a vertical borehole to discontinuities mapped using photogrammetry in a vertical, 10 m wide shaft located 20 m from the borehole to assess whether the properties of the borehole data could be indicative of the persistence differences observed in the shaft. The goal of the work was to identify if a scaling relationship existed that could either reduce censoring bias or be useful for persistence estimates. The study showed that attempting to scale a set of borehole discontinuities to match the persistence observations from the shaft, without directly addressing censoring bias, could not be done with more certainty than the error introduced by the biases discussed above.

This paper identifies the opportunity to link particular discontinuities across data sources, rather than inferring similarity from their properties in isolation from each other, to address censoring bias and help practitioners identify persistent or pervasive sets.

3 Methodology

3.1 Overview

This section describes the plane fitting analysis. Planes are fitted across data sources, and measured discontinuities from neighbouring data sources are compared with each other. The steps are as follows:

1. Organise and index the data from each source.
2. Calculate the unit vector of each discontinuity.
3. List all possible combinations of discontinuities connected across the data sources (i.e. three boreholes, two boreholes and mapping data, solely mapping data, etc.).
4. Fit planes through all discontinuity combinations listed in step 3.
5. Calculate the average orientation of the three discontinuity measurements.
6. Compare the orientation of the fitted plane to the measured orientation of the discontinuities.
7. Plot a stereonet of the remaining poles.
8. Assess the bias zones.
9. Plot the planes with good agreement between the fitted planes and the individual measurements in three-dimensional space using their centroid.

3.2 Step 1: organise the data

Data needs to be georeferenced and contain at least the orientation of the discontinuity. Borehole data can be georeferenced using the downhole survey and depth along the hole axis, and mapping data collected through photogrammetry will include the centroid of the plane. The user may also want to include other attributes that may be useful measures of a discontinuities importance to filter the data. Doing so introduces bias, but it may be required for computation efficiency.

3.3 Step 2: calculate the unit vector of the discontinuity

The comparison between discontinuity measurements and the fitted plane is done by comparing their angular distance. Angular distance is the normalised angle between two vectors (Figure 1). Each discontinuity has a vector, and the angle of intersection between these two vectors is the angular distance. A unit vector is used in the angular distance calculation, rather than a vector, because only the vector direction is used in this process.

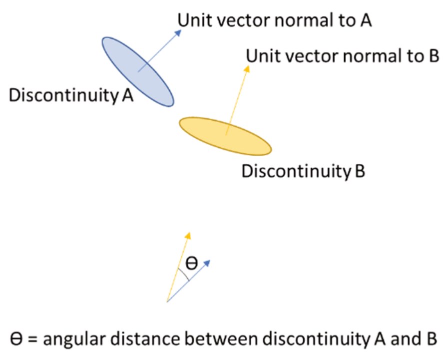


Figure 1 Example representation of angular distance between two unit vectors

3.4 Step 3: list all possible discontinuity combinations

Modern computing power allows for batch-processing large quantities of data that previously would have been prohibitively time consuming. Either a script or Excel function can be used to list all possible combinations of discontinuities present in the data sources. If input boreholes are named A, B, and C, for example, and the discontinuities are numbered 1 through *n* from top to bottom in each hole, the first combinations are (A1, B1, C1), (A1, B1, C2) through (A1, B1, C*n*), followed by (A1, B2, C1) through (A1, B2, C*n*), and the final combination is (A*n*, B*n*, C*n*).

Step 3 is a good opportunity to apply some computational efficiencies like storing the data in an array and inserting logic to only record discontinuity combinations less than a certain angular distance, as boreholes that are several hundred metres in length could yield a million or more combinations.

3.5 Step 4: fit plane through each combination

A plane is fitted through each discontinuity combination by either numerically fitting a plane through the centroids or using a three-point problem calculation. A typical mathematical solution to a three-point problem is a cross-product of two vectors. The vector between discontinuity centroid A1 and B1 must lie on the same plane as the vector between discontinuity centroid A1 and C1. The cross-product yields the attitude of the vector perpendicular to the plane that contains these two vectors, or the strike and dip of the plane connecting discontinuities A1, B1 and C1.

3.6 Step 5: calculate the average orientation of each combination

An average orientation for the three discontinuities in each combination is calculated to allow comparison with the corresponding fitted plane. There is likely to be some variability in the dip and dip direction even for well matching discontinuity combinations. Comparing a single average value of the measured orientations to a single value of the fitted plane orientation is a step to both filter out poorly matching measurements and provide an estimate of the fit quality. This step is done with a basic averaging of the measured dip directions and dips.

3.7 Step 6: compare the orientation of the fitted plane to the average orientation of the discontinuities in each combination

For each combination, the angular distance between the average measured orientation and the fitted plane is used to filter out poor matches. This step will require an understanding of the expected discontinuity waviness and roughness to select an appropriate filter. For example, filtering out combinations with angular distance values greater than 5° may only leave planar and smooth discontinuities if the data sources are far apart. Setting the filter too high may leave combinations that are poor matches. This step will require iteration and comparison to the borehole or mapping stereonets to check that the resulting pole combinations make sense.

3.8 Steps 7 and 8: plot a stereonet of the well-matched poles and assess the bias

The average orientation of the filtered discontinuity combinations are plotted on a stereonet. This stereonet will provide the practitioner with the means to interpret three things:

1. The discontinuity orientations that were not possible to sample with the borehole or outcrop locations. Bias zones will be evident where the practitioner will note that this methodology omits some discontinuity orientations. These bias zones are a function of both the borehole or outcrop orientation and the spacing between data sources.
2. Pole clusters that survive the filtering represent either discontinuities persistent across the data sources, or non-persistent discontinuities that are sufficiently pervasive to link together.

3. Pole clusters that are filtered out and are not in the bias zone, but are present in the stereonets of measured data, are not persistent across the data sources. This may provide a justification for applying some degree of rock bridging to the set.

3.9 Step 9: plot the centroid and orientation of the well-matched discontinuities

The location and orientation of the persistent or pervasive discontinuities can be plotted in a three-dimensional viewing software. This provides the practitioner with a useful depiction of the elevation range that certain structural fabrics are present, which can be useful for zone anisotropies in stability models or assessing structural domain boundaries.

4 Example application

An example is provided to demonstrate how the stereonet developed through the plane fitting analysis compared to borehole and mapping data. The example is from an open pit slope with three oriented boreholes with televiewer data through an area that has since been mined and mapped with unmanned aerial vehicle photogrammetry. The example demonstrates the process using boreholes alone and uses the stereonets of the mapping and individual boreholes to validate the results. Stereonets shown in the example are lower hemisphere, equal area stereonets with Kamb contouring (Vollmer 1995).

4.1 Example: connecting borehole data

The example features three boreholes (Table 1) with televiewer data drilled at different orientations and through the same structural domain (Figure 2).

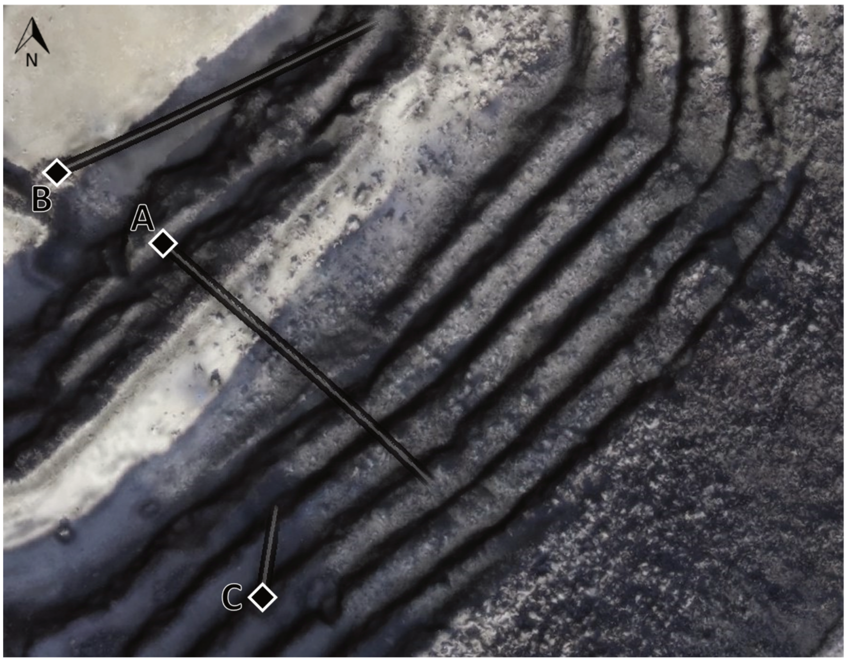


Figure 2 Drillhole locations

Table 1 Borehole information

Borehole ID	Length (m)	Trend/plunge (°)	Distance from hole B collar (m)	Distance from hole C collar (m)
A	560	134/-70	35	261
B	520	065/-75	0	275
C	280	014/-68	275	0

Plotting all possible combinations of televiewer measurements (Figure 3) yields a zone of the stereonet that can be assessed with this methodology, and another zone of discontinuity orientations that cannot intersect all three boreholes. The typical range of hole dips that can be successfully televiewed will yield similar bias zones to steep structures but will effectively sample shallow and moderately dipping sets that are typically problematic for inter-ramp scale analyses. Figure 3 also schematically provides the photogrammetry data proximity to the boreholes.

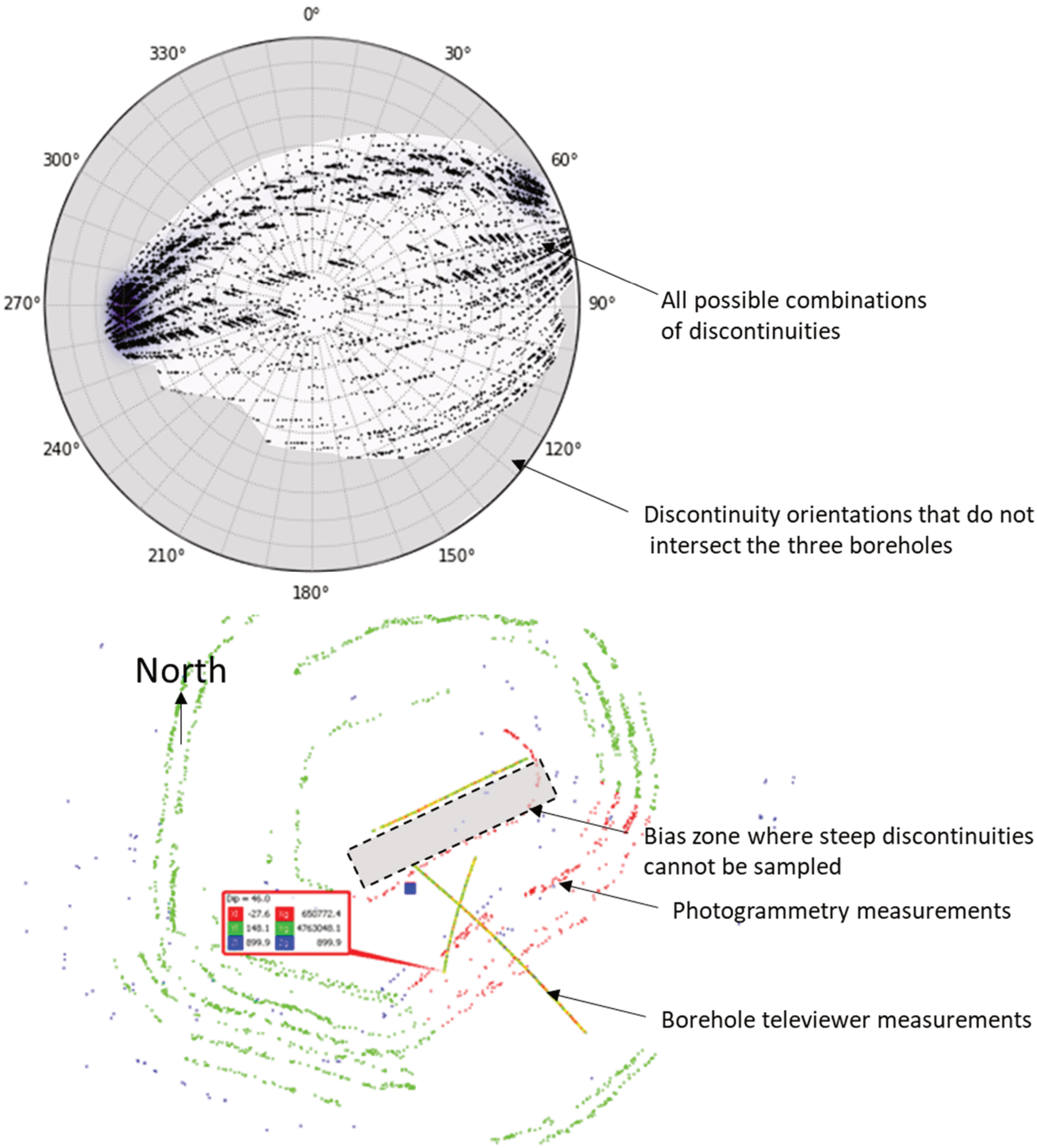


Figure 3 Stereonet of all possible measured discontinuity combinations and bias zone of discontinuities that cannot be sampled by all three boreholes (top image). Bottom image is a plan view of photogrammetry data (points) and borehole televiewer data (lines) showing a zone between boreholes where steep discontinuities will not be sampled by all three boreholes

When these combinations of televiewer measurements are filtered by angular distance, four preliminary pole clusters emerge of discontinuities that can be connected across the three boreholes (Figure 4). The example in Figure 4 applies an angular distance filter of <15°, and if the filter is reduced to <5°, the four pole clusters remain with less variability in the clustering (Figure 5). Reducing the filter to <5° nearly eliminates the northeast dipping set which may be indicative of too fine a filter.

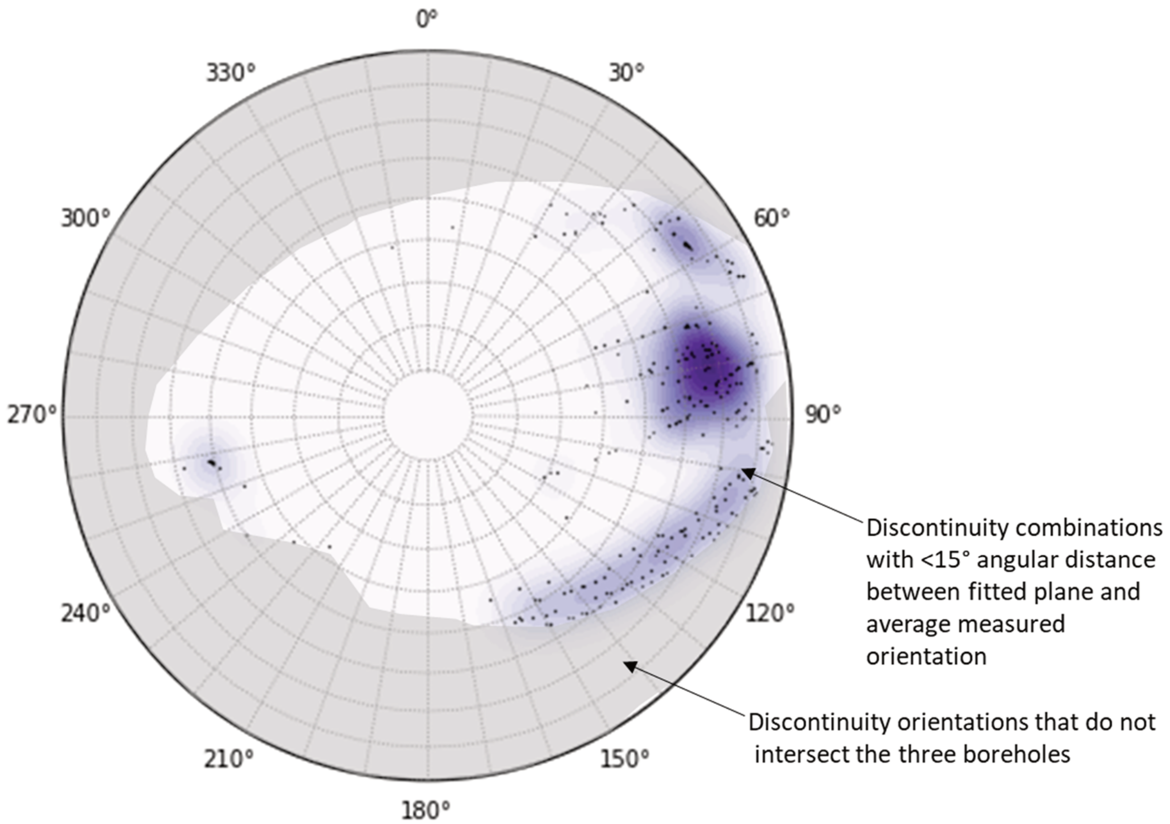


Figure 4 Stereonet of discontinuity combinations with angular distance <15°

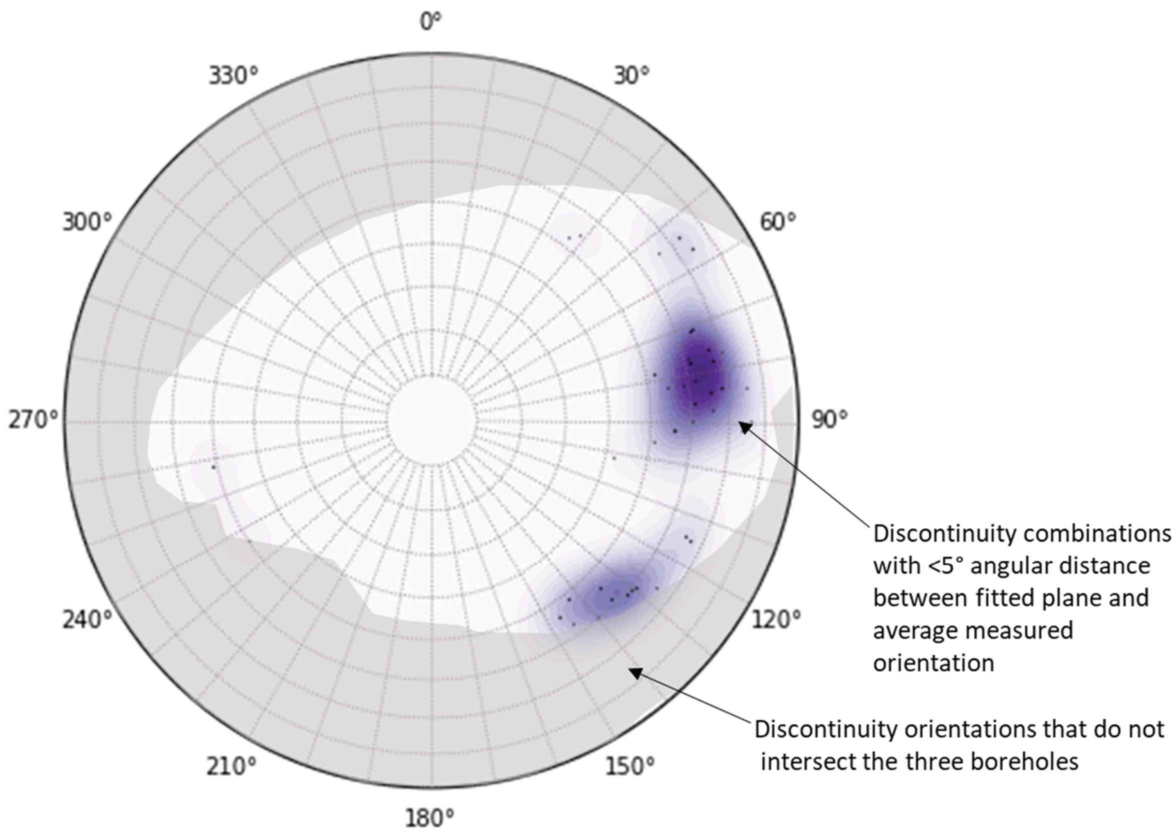


Figure 5 Stereonet of discontinuity combinations with angular distance <5°

The four pole clusters interpreted to persist across boreholes match the pole clusters in the measured borehole televiewer and photogrammetry data (colourful ovals on Figure 6), and are helpful to rank sets that are strong in one data source and weak in another. For example, the yellow and green sets are relatively strong in the borehole data and the two versions of the plane fitting analysis, but weak in the photogrammetry. These sets are perpendicular to the wall dip direction and less likely to be sampled by photogrammetry.

In the borehole televiewer stereonet, the discontinuities of the red set are scattered and could be interpreted to represent multiple distinct sets. If only borehole data was available and fitting analysis was not performed, this set would likely be interpreted to be insignificant or several less significant sets. However, in the plane fitting analysis stereonets generated using the same borehole data, the red set is the strongest set present. The red set is notably also the most prominent set in the photogrammetry stereonet. Comparing discontinuities common to boreholes, rather than independent discontinuities grouped on a stereonet, gives credibility to the importance of these sets that would otherwise have limited persistence information.

Another useful observation from the plane fitting analysis is the moderately dipping sets that are present in the measured data (black dashed ovals on Figure 6) are well within the bias zone but do not persist across the boreholes. These may be candidates for applying some cohesive strength such as rock bridging.

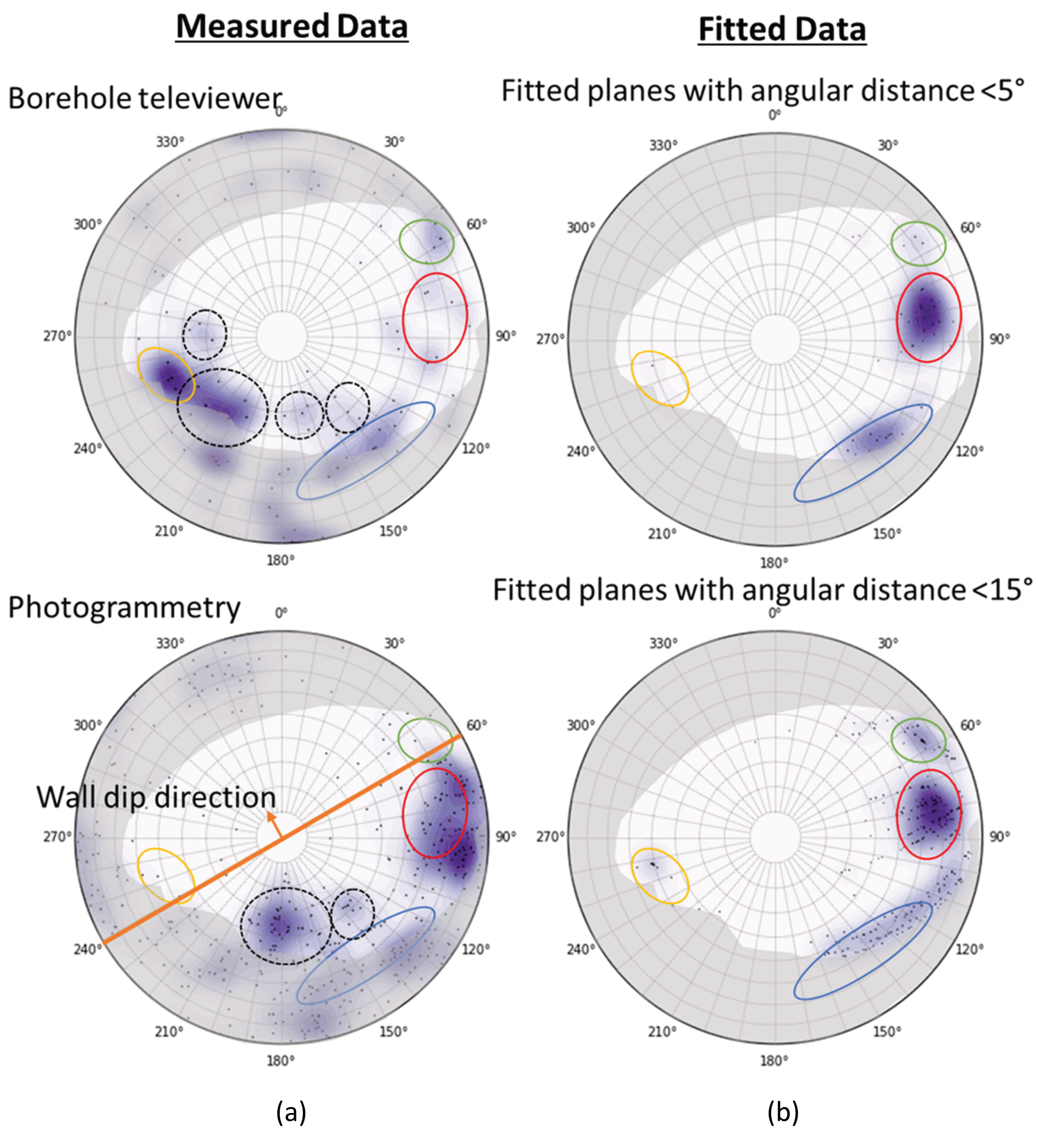


Figure 6 Comparison of (a) measured discontinuity orientations to (b) poles from the plane fitting analysis

Plotting the fitted planes in three-dimensional space with the boreholes and the mapping data allows for identifying elevation zones of similarly oriented persistent or pervasive discontinuities. The coloured arrows in Figure 7 are schematic representations of the plane vectors showing that the dominant fabric is changing with depth and there is an opportunity to zone anisotropies in stability models. The planes can also be overlain on the photogrammetry model or compared with photographs to validate the interpreted plane orientations are occurring in the benches (Figure 8).

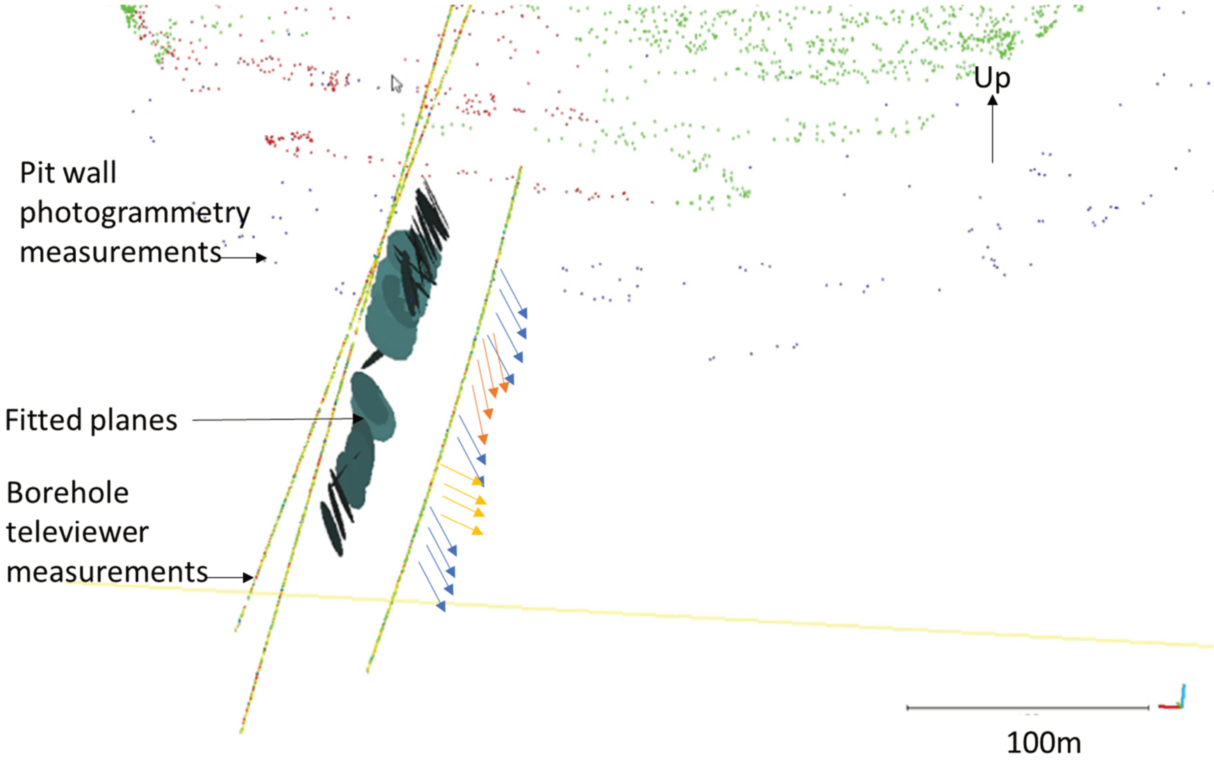
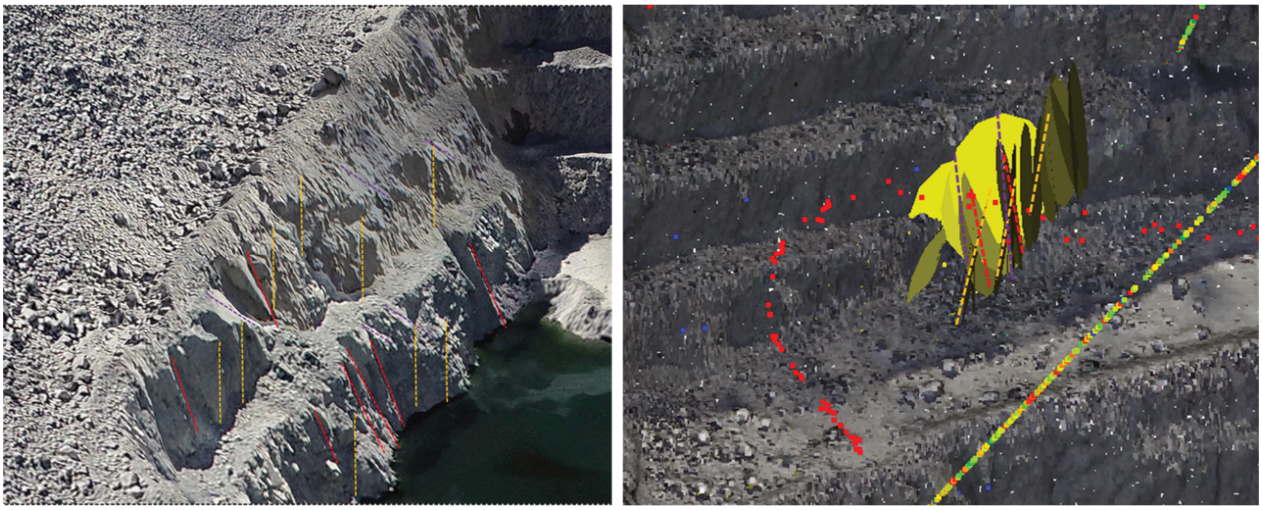


Figure 7 Fitted planes plotted in three-dimensional space showing groupings of persistent or pervasive discontinuity sets (coloured arrows)



(a) (b)

Figure 8 Comparison of sets observed (a) in the bench and (b) the fitted planes

5 Discussion and limitations

The proposed methodology provides a means to reduce censoring bias by extending discontinuities through the rock mass to neighbouring data and assessing how well their orientation matches with the intersected discontinuity. Well-matched discontinuities may be a single through-going structure, or discontinuous structures that are sufficiently pervasive to link up. Regardless, the sets that survive the filtering may be considered important for inter-ramp scale open pit slope assessments. Similarly, the sets that are prominent in the borehole or mapping data but are filtered out by this methodology may still be important for inter-ramp stability, and good candidates to consider shear strength adjustments such as rock bridging.

This methodology is reliant on the data density available, spacing of the boreholes, variability in borehole orientation, and elevation range where data is present. Borehole data must be present over similar elevation ranges and are biased to steep discontinuities. Bias zones increase with distance between boreholes.

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