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Visualising bias of structural orientation data

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Abstract

Structural discontinuities represent an essential component of the geotechnical model for rock slope design. The bias associated with structural orientation data collected from different sources is reviewed, and existing methods of understanding and overcoming this bias are discussed. An alternative method of visualising the bias is presented. This method can be applied to single drillholes, datasets derived from multiple drillholes and scanlines, face mapping or combinations of multiple sources (e.g. a combination of drillholes and mapping data). The method provides a graphical presentation of the structural orientation bias within the selected dataset. The visualisation allows identification of areas of the stereonet in which discontinuities may be under-represented and enables consideration of potential methods to reduce the associated bias. The technique assists the geotechnical designer in understanding whether datasets selected for geotechnical analysis are representative and provides an opportunity to account for the bias.

Keywords*: structural data, orientation bias, stereonets, Terzaghi correction, sampling weight*

1 Introduction

Structural discontinuities represent an essential component of the geotechnical model for rock engineering design. Data on the orientation of the discontinuities is collected through the sampling of either linear (drillholes and scanlines) or planar features (exposed rock surfaces in natural terrain or excavations). The orientation bias associated with linear surveys has long been recognised, with a widely adopted correction proposed by Terzaghi (1965). Various authors have reviewed and extended the concepts to include planar sampling surfaces and more recently developed sampling techniques (Park & West 2002; Laing 2005; Weir 2012; Fowler 2013).

The understanding of orientation bias is critical when considering orientation data for geological or geotechnical analysis and design. Practitioners routinely combine data from multiple drillholes (both televiewer (TV) and drillcore derived) and data from the mapping of extensive areas with variable wall orientations. The current methods for visualising and correcting orientation bias do not extend to these situations. Rarely when data is combined in structural domains is orientation bias mentioned, except to acknowledge that it exists.

This paper focuses on the bias resulting from the orientation of structures relative to the sampling geometries. Several other biases can result from the collection of structural orientation data; the reader is referred to Brown (2007) for a thorough discussion of these biases.

2 Orientation bias

2.1 Review

The orientation bias of sampling techniques identified by Terzaghi (1965) is the result of discontinuities of different orientation intersecting a linear (or planar) sampling method at differing angles. At the extremes, some will be normal to the sampling line and some will be parallel to it. The closer to parallel the discontinuity, the shallower the angle at which it intersects the sampling line, the less frequently intersected the plane will be, and the greater the apparent spacing. Planes normal to the sampling line will be intersected at their true spacing, as illustrated in Figure 1.

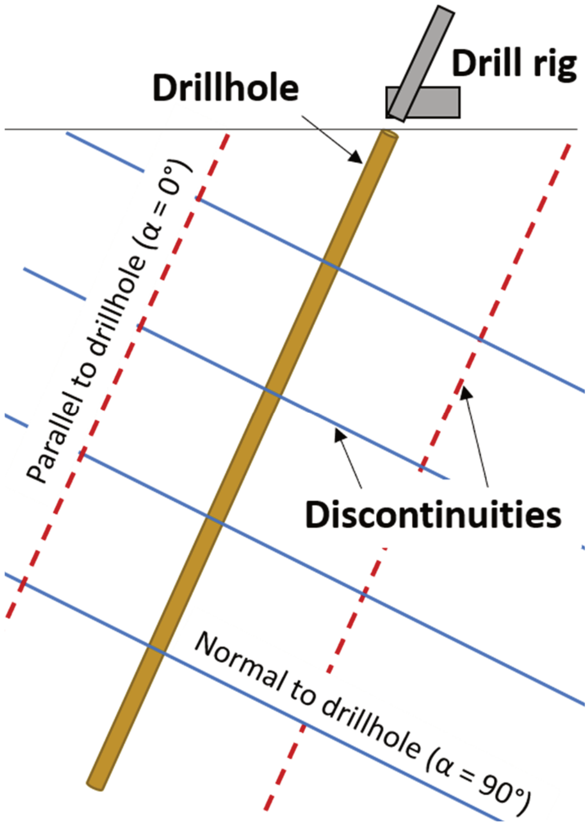


Figure 1 Sampling line (drillhole) with discontinuity sets at angles parallel (α = 0°) and normal (α = 90°) to the sampling line

The orientation bias can be related to the angle between the sampling line and the discontinuity plane (e.g. Wylie & Mah 2004; Figure 1) or the sampling line and the normal to the set (e.g. Park & West 2002; Wang & Mauldron 2006). The author uses the angle between the sampling line (or plane) and the discontinuity plane. This angle is equivalent to the α angle recorded when logging drillcore and is preferred for that reason (it is noted that this is not equivalent to the α angle referred to by Wang & Mauldron).

Terzaghi (1965) proposed a correction for the orientation bias resulting from this geometrical effect as applied to the weight of discontinuities (for contouring or analysis) presented in Equation 1. This is commonly referred to as the Terzaghi weighting. The correction can also be presented relative to defect set spacing as presented in Equation 2.

$$N_{TW} = N/\sin\alpha = N \cdot cosec\,\alpha \tag{1}$$

where:

N_{TW} = weighted number of discontinuities, corrected for orientation bias.

N = sampled number of discontinuities represented by the data point (often 1).

α = the angle between the discontinuity plane and the sampling line (°).

$$S = S_{APP} \cdot \sin\alpha \tag{2}$$

where:

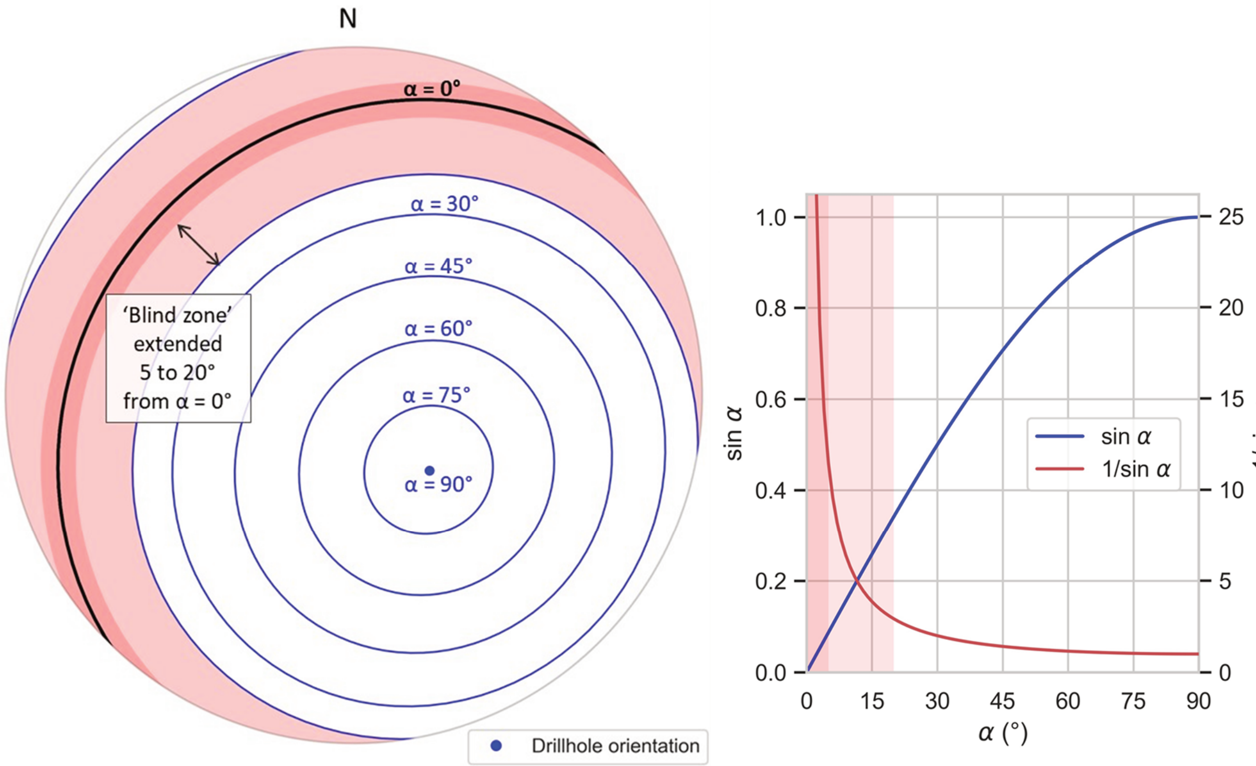
S = true spacing between discontinuities of a single set.

S_{APP} = apparent spacing of discontinuities of a single set measured along the sampling line.

Figure 2 presents the α angles relative to a drillhole and the relationship of α with sin α and Terzaghi's weighting. As can be observed in Figure 2b, '1/sin α' tends to infinity as α approaches zero. A cutoff value of α of 15–20° is generally used to limit the extreme effects of correction when applying a Terzaghi weighting below these α angles.

Terzaghi also noted a 'blind zone' formed by all the planes that parallel the sampling line, where α = 0. The actual 'blind zone' can be plotted as a line formed by the poles to all planes which parallel the sampling line; the 'blind zone' is generally extended 5–20° on either side of this line, as shown in Figure 2a. The extension of the 'blind zone' results from the observed absence of structural orientation data within this zone from linear sampling. This is contributed to by:

- The infrequency of potential structural intersections in this zone, due to the high angle with the sampling line.
- The extreme effects of correction (tending to infinity, Figure 2b) with increasing proportional error (Wang & Mauldron 2006) can distort data.
- The tendency for the fracturing of drillcore where subparallel discontinuities are encountered with consequent loss of drillcore orientation (not applicable to scanline and TV derived data.)



(a) (b)

Figure 2 (a) Stereonet of drillhole plunging 65° to southeast with 'blind zone' and small circles representing various alpha angles; (b) Relationship between α, sin α and 1/sin α demonstrating the impact of applying a Terzaghi weighting

Within the 'blind zone', infrequent data points may be present, and these should be used cautiously to interpret structural patterns within this zone wherever possible.

Weir (2012) and Fowler (2013) discuss other orientation related biases they have experienced with downhole TV tools and photogrammetric/laser mapping. The author recommends that practitioners review data for evidence of these biases. In the author's experience, some of these biases may be minor compared with those introduced by the automated or manual interpretation of discontinuity orientations from such sources. The development of comprehensive data collection procedures and thorough data review is recommended to help address such issues.

Laing (2005) considered the 'data gap' resulting from drillhole arrays aligned in a shared orientation and extended this to various arrays of drillholes, 2D and 3D topography and excavations, as shown in Figure 3. Figure 3 is a valuable reference concerning 'blind zones', however, it does not illustrate areas of orientation bias beyond unsampled zones.

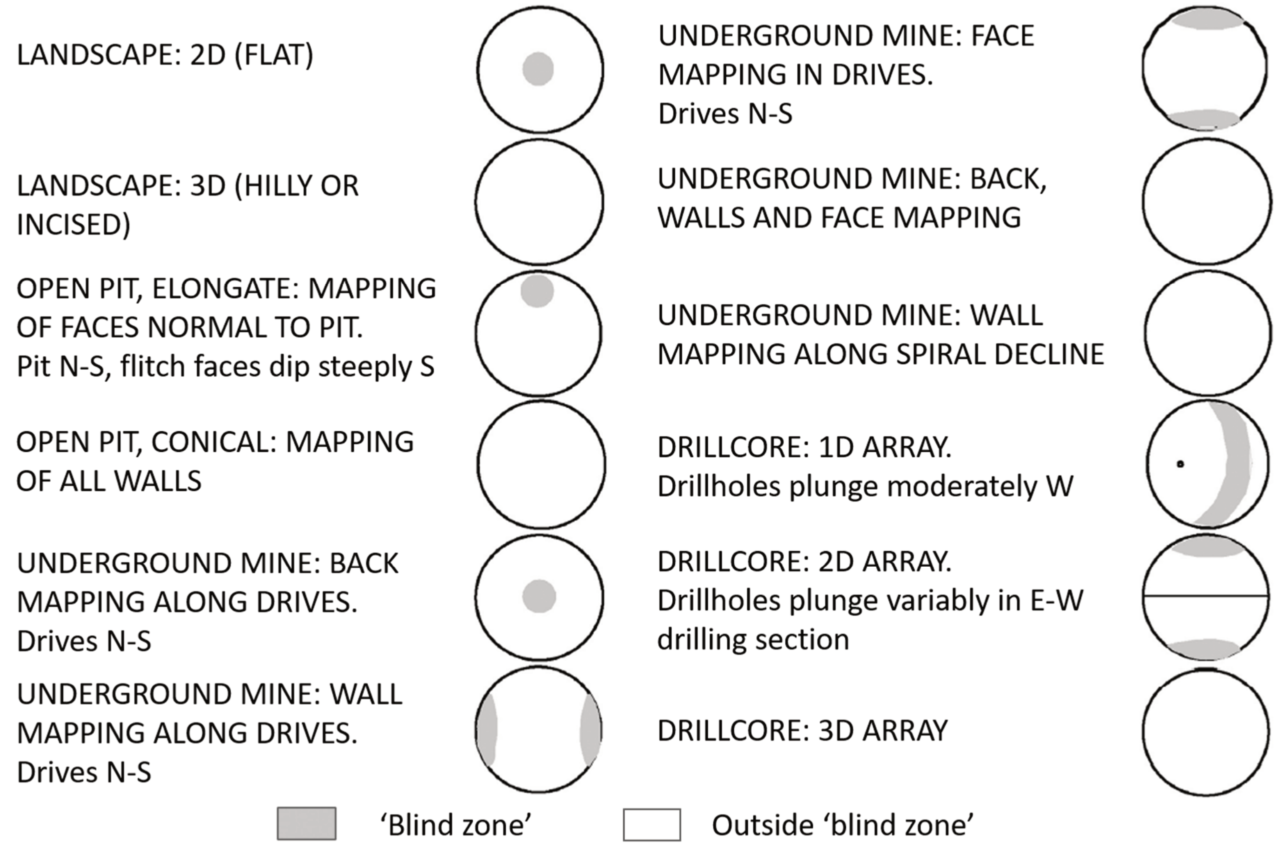


Figure 3 The 'data gap' (or 'blind zone') for the most common sampling topographies (after Laing 2005)

2.2 Further considerations when applying the Terzaghi weighting

2.2.1 Curved drillholes and pre-collars

'Blind zones' are routinely shown on stereonets when data is presented for single drillholes. The 'blind zone' is represented by a small circle (or cone) centred on the hole orientation. Few drillholes are entirely linear and some curve significantly. In such cases, the 'blind zone' can be drawn relative to the vector average hole orientation, or more appropriately, the average hole orientation from intervals in which structural data has been collected.

Intervals that should be considered for exclusion from the vector average hole orientation include pre-collars, areas where core orientation was not achieved, and zones where observation of the drillhole wall is obscured (by drilling mud or low-quality image) in TV survey. This distinction can be significant for long drillholes collared at the crests of large open pits, as shown in Figure 4. The upper 315 m of this hole was pre-collared, and the appropriate vector average orientation and the resultant 'blind zones' for this drillhole vary from the overall average.

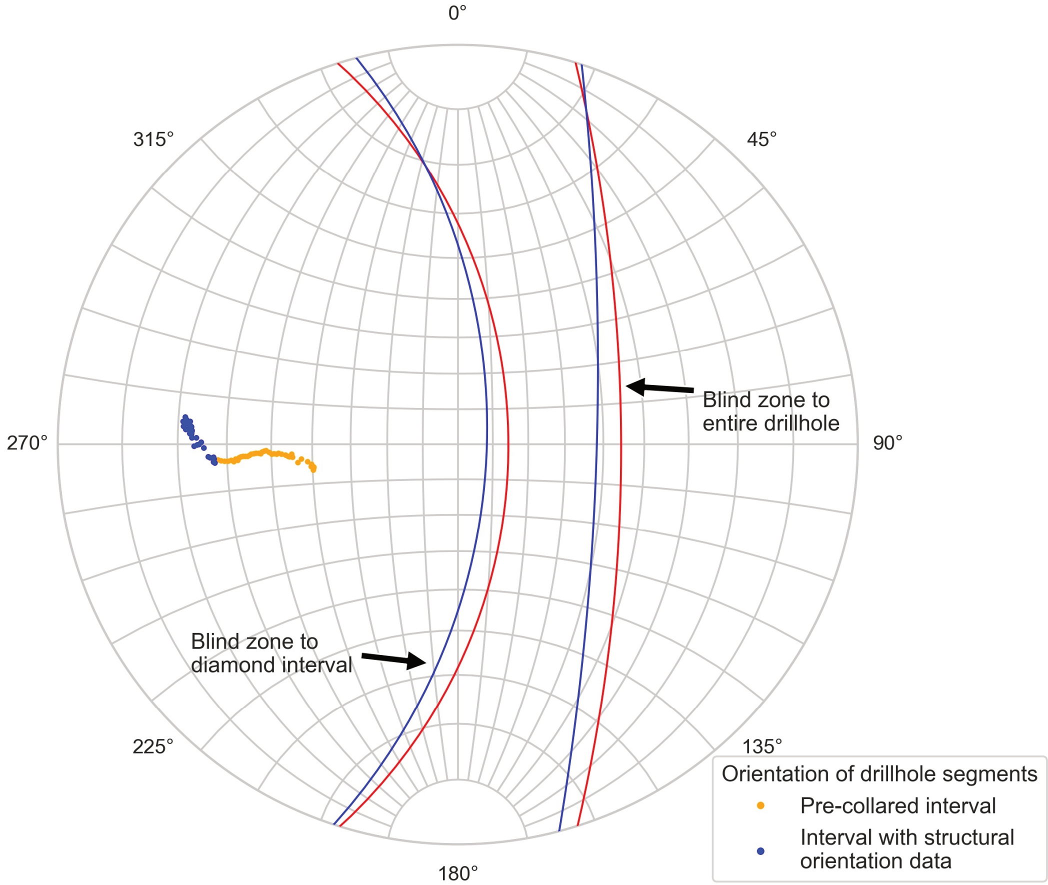


Figure 4 1,055 m drillhole showing 'blind zones' as small circles (lines) drawn at 75° to average drillhole orientation: entire drillhole (red) and lower oriented intervals (blue). Points show surveyed hole orientations

2.2.2 Sample confidence

In considering whether to apply the Terzaghi weighting to your dataset, it is beneficial to compare structural data per drillhole contoured with and without the Terzaghi weighting applied. Data can then be reviewed to check for artificial effects and possible amplification of low confidence or suspect data points. It is considered appropriate that the Terzaghi correction be applied where representative sampling is achieved (outside the 'blind zone'), orientation confidence is high, and evidence for errors is minimal. To apply the Terzaghi correction to TV derived orientation data, it may be necessary to calculate the alpha angle. This angle can be calculated as 90° minus the angle between the drillhole orientation and the pole to the discontinuity plane.

A representative sample is required to characterise the variability and nature of discontinuities in different sets. In applying the Terzaghi weighting and selecting a 'blind zone' cutoff, it is worth considering how well-sampled any identified defect sets are. Priest & Hudson (1976) stipulated a sampling length of 50 times the mean spacing to suitably characterise the spacing distribution, which implies sampling at least 50 discontinuities from the set. Fillion & Hadjigeorgiou (2018) related the sample size required to the levels of geotechnical data by study stage proposed by Read & Stacey (2009), suggesting that:

> *"The minimum number of orientation data required to estimate the orientation of a single joint set with a 2° angular limit for the different geotechnical level status are ≥15 joints for Level 1; 30–40 joints for Level 2; 35–75 joints for Level 3; 55–90 joints for Level 4; and ≥90 joints for Level 5."*

How many times a set is intercepted by a linear sampling method is a function of the length of the sample line, the discontinuity spacing, and the discontinuities' orientation relative to the sampling line. If the discontinuity spacing is known or assumed, how well defect sets are likely to be defined based on their orientation relative to the sampling line can be displayed on a stereonet. In the example shown in Figure 5, small circles are drawn representing the limits of well-defined (>50: green) and less well-defined (20–50: orange) defect sets based on a planned 110 m drillhole and an estimated average joint spacing of 2 m. The author has found this style of representation valuable during the planning of geotechnical investigations; in this case, the illustration justified extending the drillhole to better sample defect sets at a greater range of orientations.

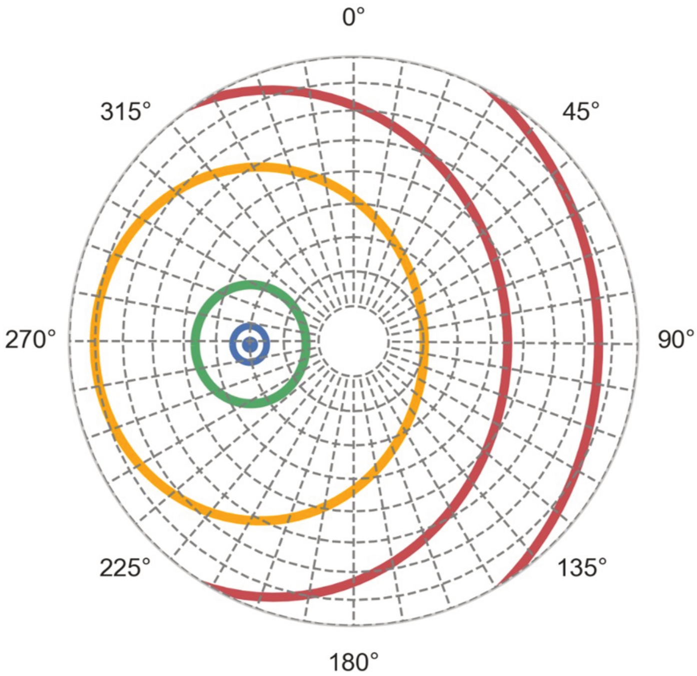


Figure 5 Representation of zones of sampling quality of discontinuity sets for a planned 110 m long drillhole plunging 60–270° and assuming a fracture spacing of 2 m. Within green line: well-defined sets, within orange line: moderately well-defined sets, beyond orange line: poorly defined sets (red: limits of blind zone)

2.3 Limitations

Structural orientation data is generally not considered on a drillhole-by-drillhole basis but is combined into larger datasets that may be used to represent structural domains or entire deposits. Combining data from multiple sampling lines introduces additional biases from variations in drillhole orientation and length. Besides the idealised examples of Laing (2005), the author is not familiar with any representations of sampling bias for combined datasets.

3 Relative sampling weight

3.1 Method applied to a single sampling line (drillhole)

An isotropic joint distribution is considered; it is assumed that a theoretical rock mass intersected by sampling would contain structures at all orientations equally. A uniform joint orientation distribution would result if representatively sampled, with no bias or ‘blind zones’. This could be presented as a stereonet of a single shade, representing a uniform sampling weight. If sampled by a single drillhole, sampling would be represented by a bullseye centred on the drillhole orientation. As identified by Terzaghi, as the alpha angle decreases away from the drillhole orientation, discontinuities become less well-sampled, resulting in a lower sampling weight. With the application of the Terzaghi weighting, this aspect is corrected, and one would see a uniform sample weighting except within the ‘blind zone’ (where the sampling weight is considered zero). These scenarios are presented on stereonets using a colourmap of the relative sampling weight in Figure 6.

The colourmap represents the relative sampling weight for each area of the stereonet, with the blind zone considered to be unsampled (sampling weight = 0).

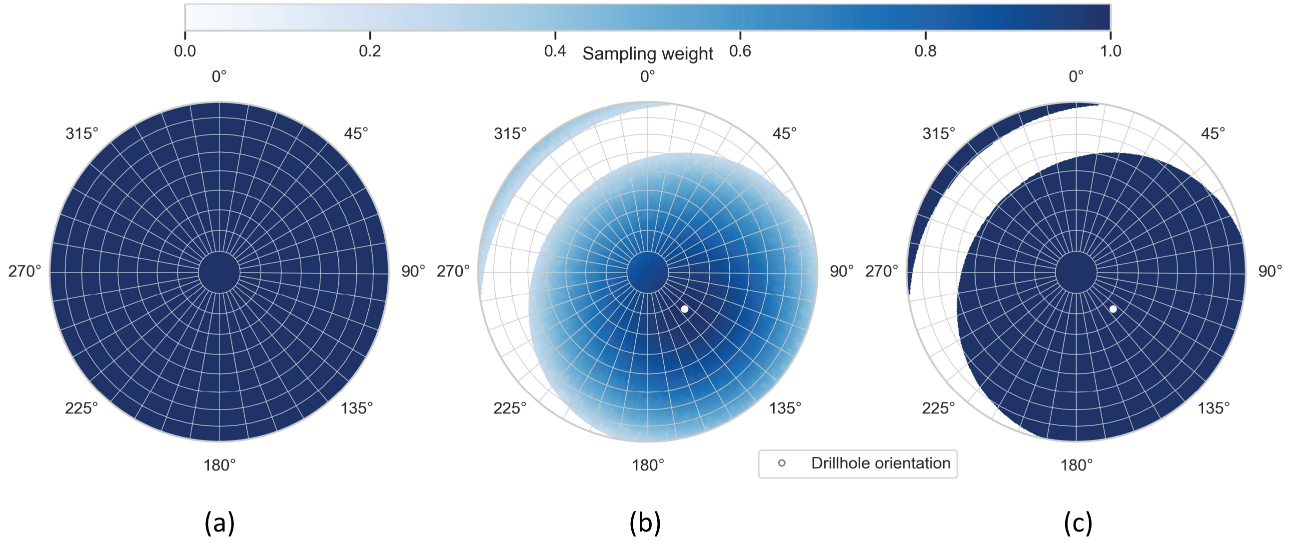


Figure 6 Sampling of structural orientations of isotropically jointed rock mass, represented using a colourmap. (a) Un-biased sampling: uniform sample weighting; (b) Sampled by a single straight drillhole plunging 65–135°; (c) Sampled by the same drillhole, with orientation bias corrected using the Terzaghi weighting. Note that the 'blind zone' is considered unsampled and has a resultant sampling weight of zero (corresponding to white)

To generate the sampling weight colourmap, points representative of all possible discontinuity orientations are compared with the direction of the sampling lines (or line segments) to allow calculation of the alpha angle to each. For each potential discontinuity orientation, the weighted sampling lengths from each sampling line (e.g. drillhole segment) where alpha is ≥15° (the selected 'blind zone' cutoff) are then summed and normalised between zero and the maximum sampling length, as per Equations 3 and 4. The points are then plotted coloured by the sampling weight. Contouring is not used in the process, which allows a more precise representation.

$$SW = \frac{L}{\max L} \tag{3}$$

$$L = \sum_{i=1}^{n} l_i \cdot \sin\alpha_i \cdot \ [\alpha_i \geq 15] \tag{4}$$

where:

SW = sampling weight for each orientation (defined by strike and dip).

L = total sampling length for each orientation (defined by strike and dip).

$\max L$ = the maximum sampling length for any orientation.

l_i = length of sampling line segment i.

α_i = the angle between the discontinuity plane and sampling line segment i (°).

3.2 Curved drillholes

The method provides a useful tool for visualising the relative sampling weight for curved drillholes. Figure 7 shows an example where each segment of the drillhole trace (for which discontinuity orientation data is collected) is weighted by its length to allow the overall sampling weight for each area of the stereonet to be calculated. The upper 140 m of this drillhole, collared behind the crest of a large open pit, were not oriented and are excluded from the data presented. The traditional representation of the 'blind zone' is shown for comparison.

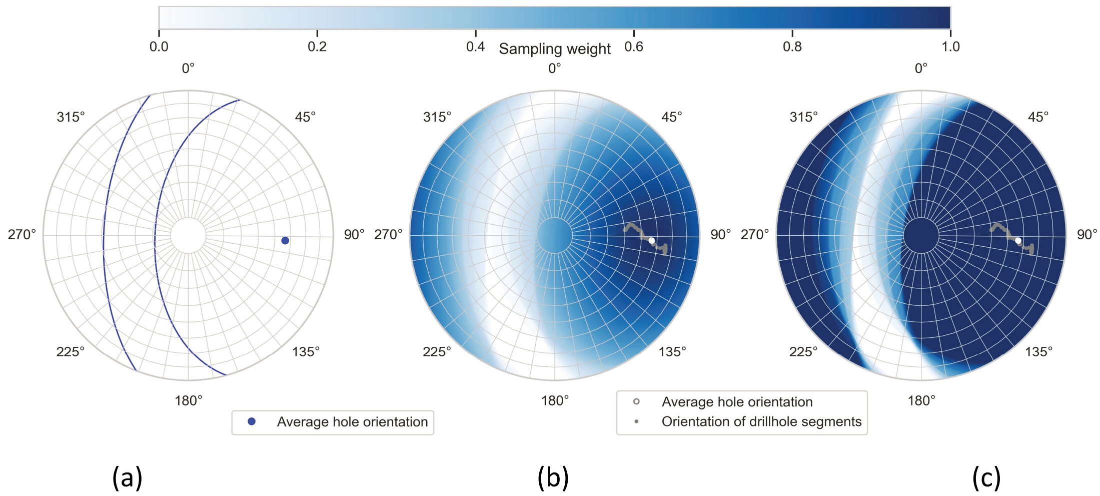


Figure 7 Stereonets annotated with: (a) 'Blind zone' drawn to vector average drillhole orientation; (b) Coloured by relative sampling weight based on curved hole orientations; (c) Orientation bias corrected using the Terzaghi weighting

The colourmaps of sampling weight presented in Figures 6 and 7 clearly show the relative sampling achieved by the drillholes; defect orientations where data is under-represented due to sampling bias can be readily identified.

3.3 Application to multiple sampling lines (drillholes)

The method can be extended to arrays of multiple sampling lines by incorporating the segments of each line and their sampling lengths. The theoretical example of Laing (2005) for a 2D array of drillholes oriented in an east–west alignment is presented in Figure 8, with colourmaps of sampling weight. Two drillholes of equal length are used in this example. The amount and orientations of zones of bias present within the resultant structural dataset are evident, with the 'blind zones' apparent as white areas in the poles. The 'blind zones' of each respective drillhole are seen to lessen the sampling weight on each side of the stereonet, where, in the case of the Terzaghi corrected dataset, a 50% sampling weight is present for large areas. If the resultant dataset were to be used for kinematic analysis of rock slope stability for north–south striking slopes, structures dipping between ~50° and 80° to the east or west would be under-represented by a factor of 2. The sampling bias present could significantly influence the results of an analysis.

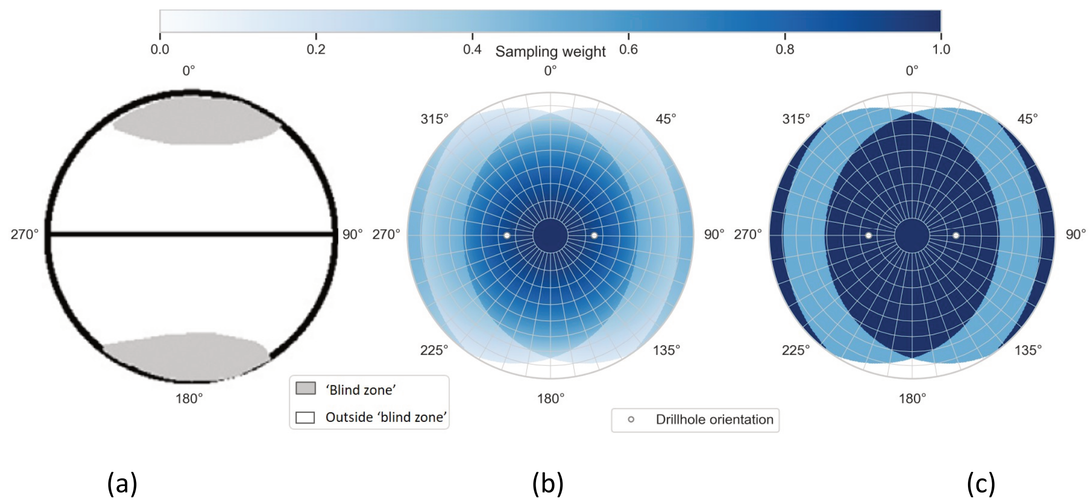


Figure 8 Representation of sampling bias from a 2D drillhole array: drillholes of equal length plunging at 65–90° and 270°. (a) 'Blind zones' presented by Laing (2005); (b) Sampling weights represented using a colourmap without application of Terzaghi weighting; (c) As (b) with orientation bias corrected using the Terzaghi weighting

Figure 9 presents the sampling bias from a 3D drillhole array comprising six drillholes plunging at 65° to azimuths 60° apart. Laing (2005) identified that the 'blind zone' is no longer present, with all possible structural orientations sampled to some degree. The sampling weight colourmaps clearly highlight that structures dipping at <50° are sampled at a greater frequency than those dipping at >50°. The average sampling weight of structures dipping at more than 55° is less than 0.6 when Terzaghi correction is applied on a drillhole-by-drillhole basis, and <0.35 when not applied. These under-represented moderately to steeply dipping structures are likely to be those most critical to structurally controlled instability modes, should the data be used for kinematic assessment.

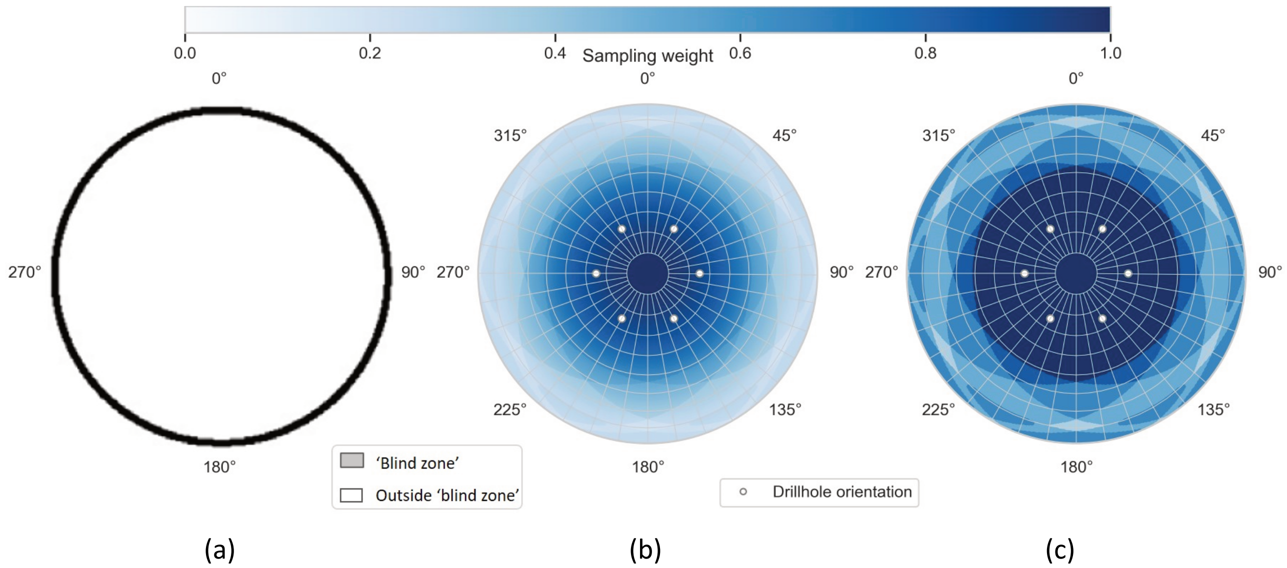


Figure 9 Representation of sampling bias from a 3D drillhole array – six drillholes of equal length plunging at 65° to equally spaced azimuths. (a) Lack of a 'blind zone' as presented by Laing (2005); (b) Sampling weights represented using a colourmap without application of Terzaghi weighting; (c) As (b) with orientation bias corrected using the Terzaghi weighting

3.4 Mapping data to sampling planes (pit walls/outcrop)

In the author's experience, the correction of sampling bias through the application of a Terzaghi weighting to data collected by the mapping of wall surfaces, either digitally or physically, is undertaken less routinely than for linear sampling. The angle between the sampling (wall) plane and the structural orientation plane can be calculated as the angular distance between the poles to these planes; the Terzaghi weighting can then be applied as for linear sampling. When considering the application of the correction to mapping data, biases associated with the sampling technique, such as the under-representation of face normal defects from digital surface mapping (Fowler 2013), should be considered.

The bias is presented for a sampling plane dipping at 70° to the south using a colourmap in Figure 10, with a 'blind zone' shown, which includes planes oriented within 15° of the sampling plane (the extent of the 'blind zone' should be considered with respect to the size of the sampling plane and the fracture density.)

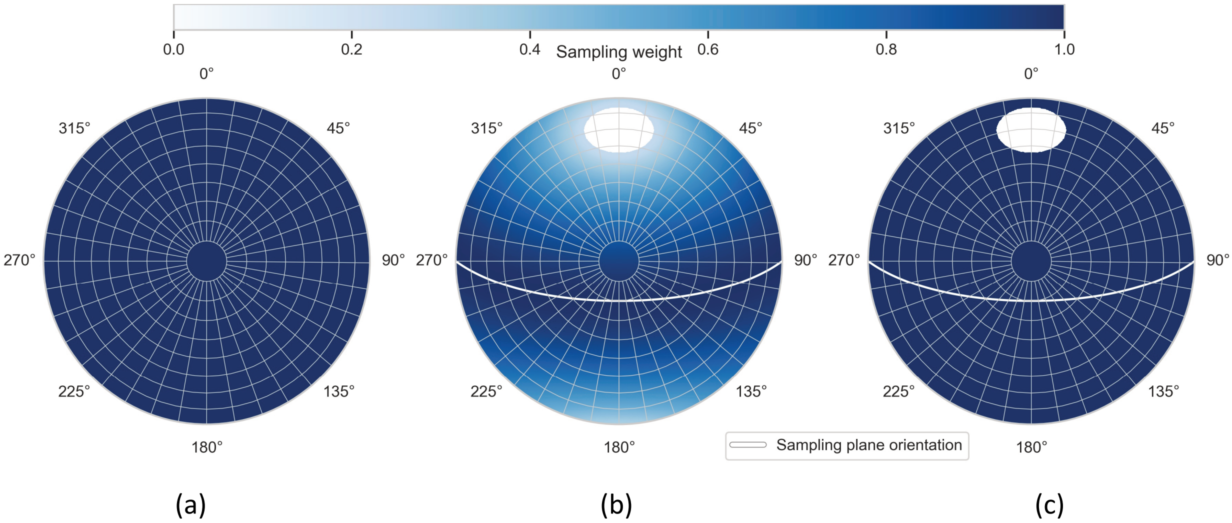


Figure 10 Sampling of structural orientations of isotropically jointed rock mass, represented using a colourmap. (a) Un-biased sampling; (b) Sampled from a planar mapping surface dipping 70–180°; (c) Sampled from the same surface, with orientation bias corrected using the Terzaghi weighting

Sampling planes used for mapping tend not to be perfectly planar, especially for digital mapping, where natural topography or benched slopes may be stepped, curved or undulating. A section of pit wall captured using photogrammetric methods to allow discontinuity mapping is presented in Figure 11a. The author extracted polygon data from a simplified wireframe mesh surface using Gem4D (BasRock 2021), as shown in Figure 11b. This data was filtered to the mapping area and reviewed to understand the sampling bias in the resultant structural dataset.

The data extracted from the simplified mesh was used to assess the bias, with the sampling weight (Equations 3 and 4) based on the area of the polygons (rather than the length of line segments). The resultant colourmap of sampling weight is presented in Figure 12. This method can be readily extended to incorporate planes at many different orientations, as might be expected from a pit wide window mapping or photogrammetric campaign.

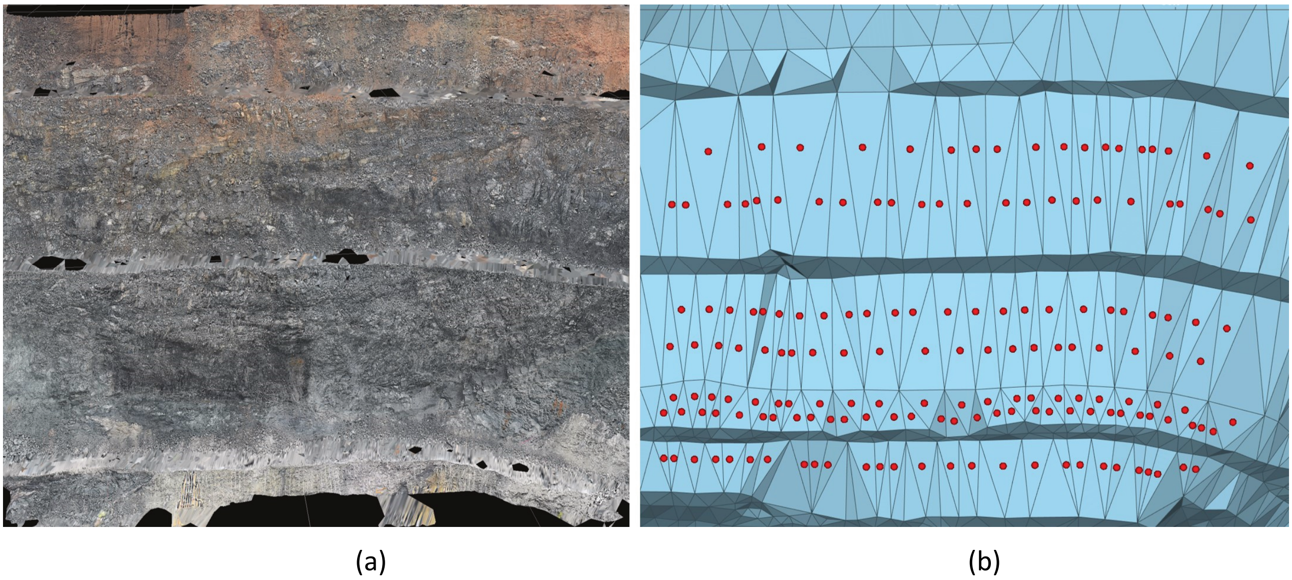


Figure 11 (a) Textured mesh of pit wall for structural data collection developed using photogrammetry; (b) Simplified mesh wireframe with centres of polygons representing the sampling planes as red spheres

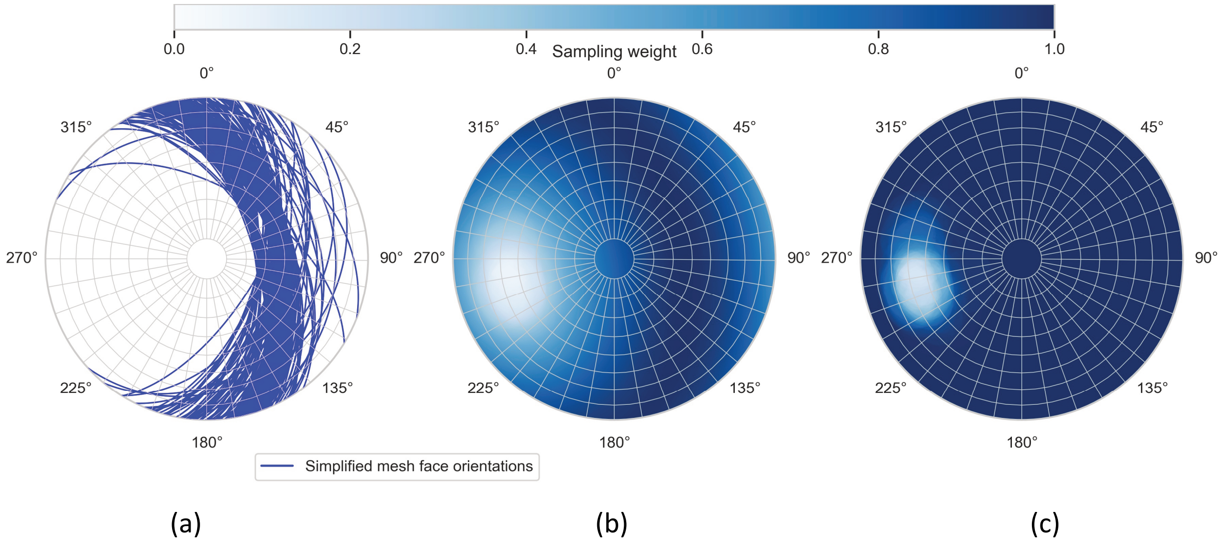


Figure 12 Stereonets annotated with: (a) Planes of polygon faces from simplified mesh (as shown in Figure 11b); (b) Representation of sampling bias as a colourmap coloured by relative sampling weight based on area of polygons from simplified mesh; (c) As (b) with orientation bias corrected using the Terzaghi weighting

3.5 Combining wall mapping and drillholes

Structural data collected from wall mapping and drillholes are often presented in combined datasets; this practice should be undertaken with caution and only after thorough consideration of the biases and limitations of each data source. The sampling bias of these combined datasets can be readily demonstrated using the presented method. In assessing the sampling weight for combined datasets, consideration needs to be given to the relative weighting of sampling from lines and planes. It is recommended the average number of discontinuities per square metre and per linear metre are compared to allow an appropriate relationship to be developed for each structural domain.

4 Correction of data for sampling bias

The relative sampling weight of data can be calculated for all possible structural discontinuity orientations. It can therefore be calculated for measured structural discontinuity orientations and applied as a correction factor.

By dividing the number (quantity) of defects represented by each structural orientation data point by the relative sampling weight for the discontinuity orientation, a correction is applied to remove the sampling bias, as per Equation 5. It is recommended that the Terzaghi weighting correction is considered as a first step and the remaining sampling bias considered subsequently.

$$N_{SW} = N/SW \tag{5}$$

where:

N_{SW} = weighted number of discontinuities, corrected for sampling bias.

N = sampled number of discontinuities represented by the data point, which may have been corrected with a Terzaghi weighting (i.e. N_{TC}).

It should be recognised that any errors within the dataset can be magnified by applying a correction and that a correction should only be applied where combining structural data can be justified (i.e. in a single structural domain). It is important to consider whether less well-represented structural orientations have been suitably sampled; a lower bound cutoff to the correction should be considered. Data within a 'blind zone' where the weighting is zero cannot be corrected. Depending on the amount of data collected, a lower bound cutoff of between 0.1 and 0.3 may be considered appropriate.

It may also be beneficial to review the structural dataset relative to the sampling weight prior to considering applying a correction. It may become apparent that the correction may be most important for a single defect set or that areas of lower sampling weight have not been suitably sampled. In some cases, correction may have a limited impact on subsequent geotechnical analysis and may be rejected as a result.

5 Examples from open projects

5.1 Example A

Example A is from a gold prospect in West Africa. The deposit consists of bedded and foliated meta-sedimentary rocks with a well-developed westerly dipping fabric. Due to the structure of the deposit, the majority of drilling undertaken plunges to the east-southeast. To allow geotechnical assessment of the hanging wall (West wall), several diamond drillholes plunging to the southwest to the northwest were drilled, and structural data was collected from the oriented drillcore.

For analysis, the designers chose to combine the structural data derived from the geotechnical drilling into the hanging wall with the structural data derived from geological drilling. Datasets were combined in order to increase the volume of structural orientation data and reduce the orientation bias by combining datasets with different drilling orientations. To further understand the sampling bias, the drillhole survey data was filtered to include only segments which had been successfully oriented. Colourmaps were created for the combined dataset and separately for the geotechnical data.

Figure 13 shows the bias associated with the combined dataset (upper) and the geotechnical drilling into the hanging wall (lower). The sampling weights of combined data can be seen to be highly biased in critical areas for hanging wall stability, i.e. the 'blind zones' of drillholes plunging to the east-southeast. Core orientation had been problematic drilling into the hanging wall, contributing to the resultant bias.

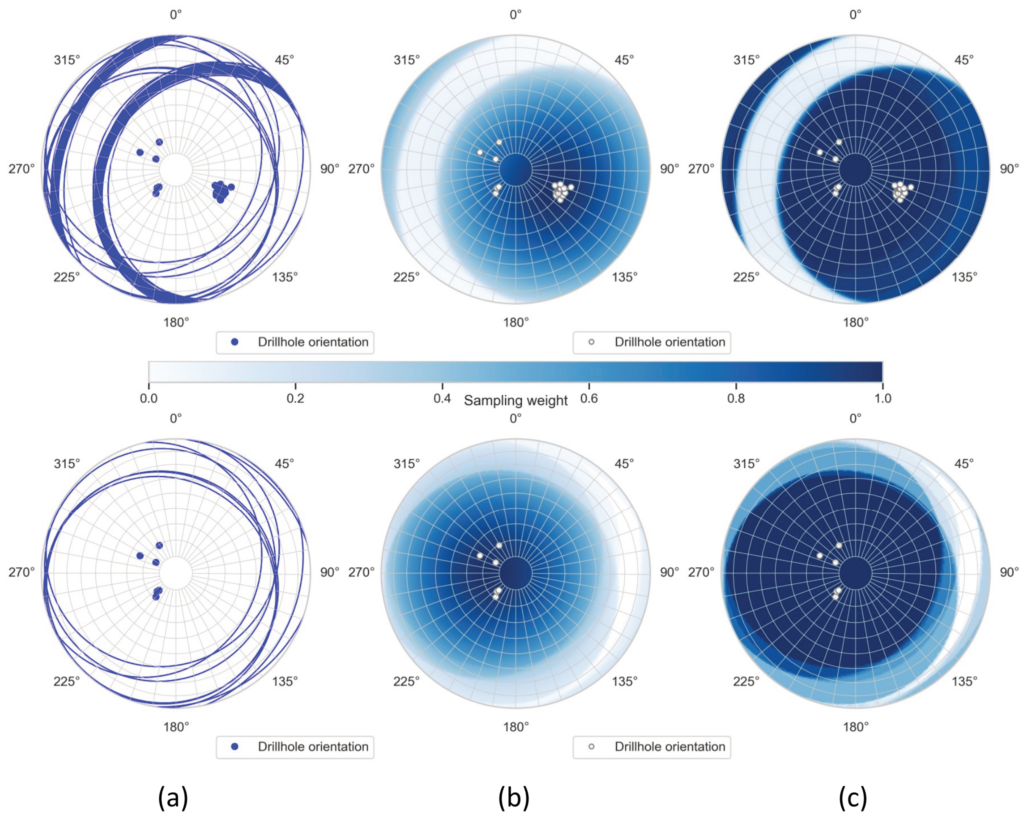
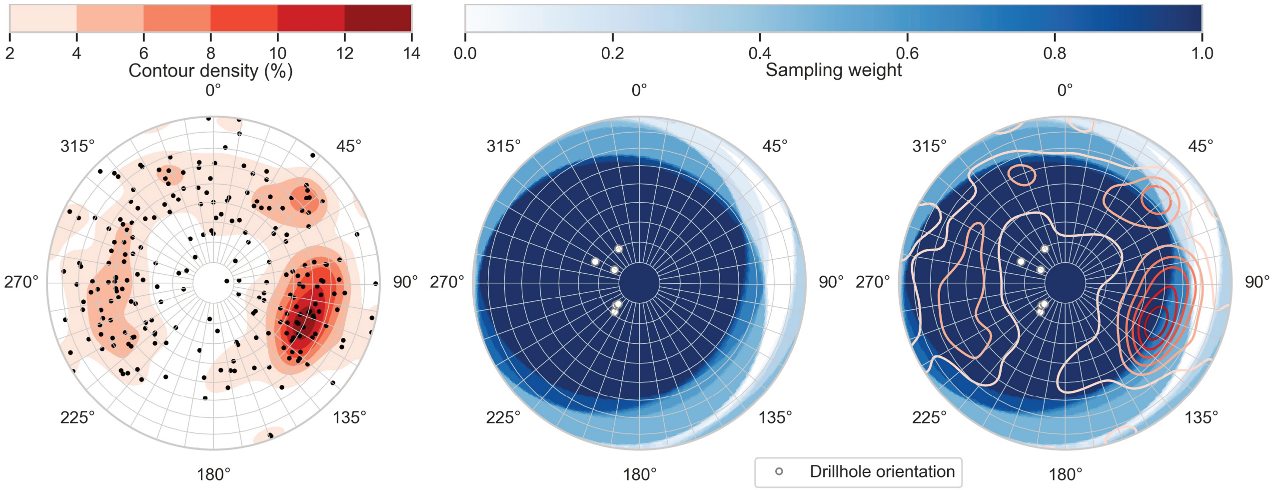


Figure 13 **Upper: geotechnical drilling data combined with geological data for the domain, and lower: geotechnical drilling into the hanging wall only. (a) 'Blind zone' drawn to vector average drillhole orientations; (b) Coloured by relative sampling weight for segments of oriented drillcore; (c) As (b) with bias corrected using the Terzaghi weighting**

Figure 14 shows the structural dataset collected from the geotechnical drilling into the hanging wall next to and overlain on the sampling weight colourmap. The dominant foliation of the deposits is clearly visible, as are the areas where samples are under-represented through the influence of the blind zones. It can also be seen that areas representing potential moderately to steeply pitward (east) dipping defect sets are well-represented.

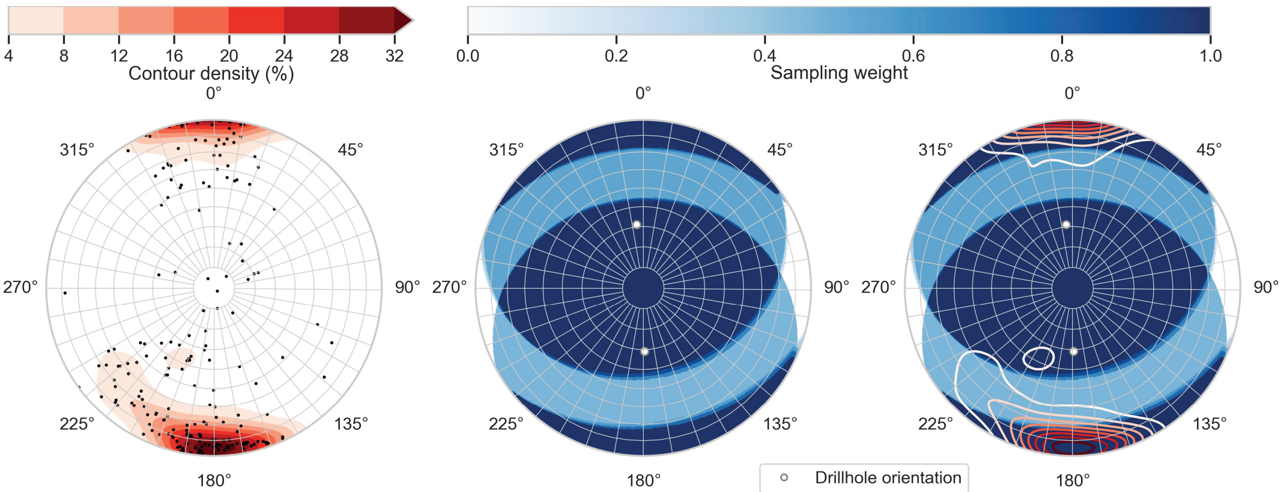


(a) (b) (c)

Figure 14 (a) Contoured discontinuity orientation data from geotechnical drilling into the hanging wall (Terzaghi weighting applied); (b) Sampling weight colourmap (with Terzaghi weighting applied); (c) Contours of collected structural data overlain on the colourmap

5.2 Example B

Example B is from a gold prospect in Western Australia. The deposit consists of fine-grained strongly foliated meta-sedimentary rocks, with a well-developed east–west striking, steeply dipping fabric. Geotechnical investigation was designed predominantly with drillholes oriented plunging north and south. Structural data was subdivided and grouped for various potential development areas along the strike of the deposit. Figure 15 presents data for a single domain with Terzaghi correction applied. The sampling bias resulting from the 2D drillhole array used for sampling can be readily observed.



(a) (b) (c)

Figure 15 (a) Contoured discontinuity orientation data from geotechnical drilling at Example B (Terzaghi weighting applied); (b) Sampling weight colourmap (with Terzaghi weighting applied); (c) Contours of collected structural data overlain on the colourmap

Figure 16 shows the data with the sampling weight correction applied. The influence of the correction can be readily observed, with the contours extending into areas of previously low sampling weight (the 'blind zones' from each drillhole). The corrected dataset was considered more appropriate for use in kinematic analysis of the north and south walls and resulted in the reduction of the design batter face angle. In this case, the application of a correction was considered appropriate, and the resultant dataset is considered to be more representative of discontinuity conditions in the domain. Further drilling to allow collection of additional data during the next stage of the study was also recommended.

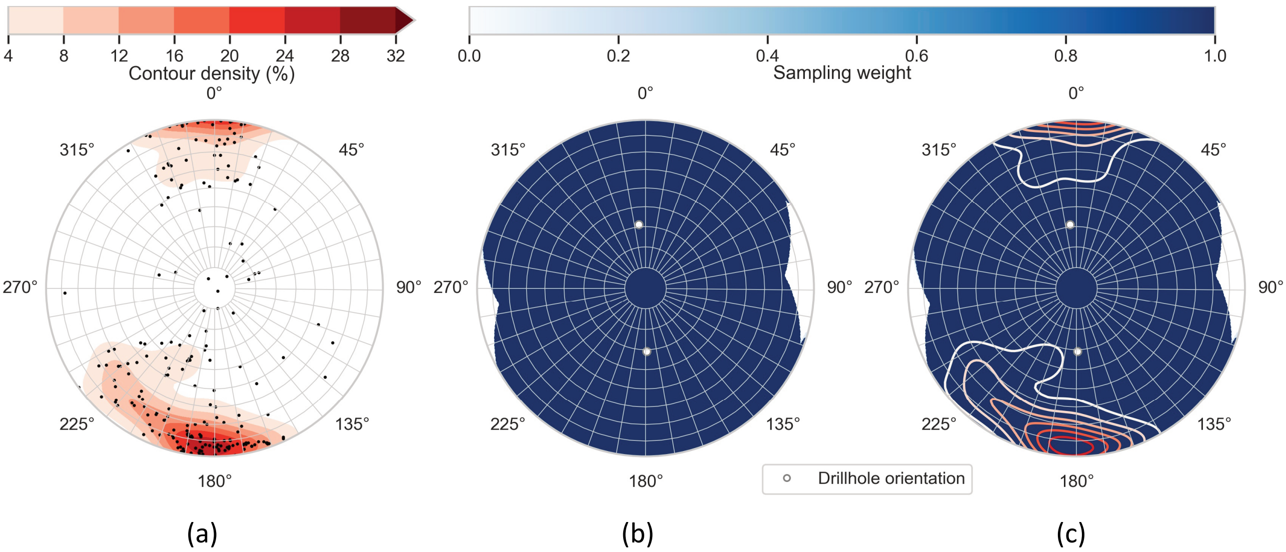


Figure 16 (a) Corrected and contoured discontinuity orientation data from geotechnical drilling at Example B (Terzaghi weighting also applied); (b) Sampling weight colourmap (with sampling bias correction and Terzaghi weighting applied); (c) Contours of weighted structural data overlain on the colourmap

6 Conclusion

A method has been presented which allows the orientation and sampling bias in structural orientation datasets to be readily visualised using a colourmap. The method complements the well-established Terzaghi weighting, the application of which is also discussed. In the resultant colourmap, areas of low sampling weight can be readily identified. 'Blind zones' are assumed to be unsampled; the extent of the 'blind zone' should be carefully considered.

The extension of the method to curved drillholes, datasets of multiple drillholes and mapping of pit walls has been demonstrated. Structural orientation datasets combined from multiple sampling lines or areas can also be visualised. Orientations under-represented within the dataset are readily identifiable.

By applying the calculated sampling weight to collected discontinuity orientation data, sampling bias against more poorly sampled orientations can be corrected. This should only be undertaken with due consideration.

Acknowledgement

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