Caving 2022 - Y Potvin (ed.)

doi:10.36487/ACG_repo/2205_72

# A review of structural data collection methodologies for discrete fracture network generation

**D Sewnun** *Australian Centre for Geomechanics, The University of Western Australia, Australia*

**J Wesseloo** *Australian Centre for Geomechanics, The University of Western Australia, Australia*

**M Heinsen Egan** *Australian Centre for Geomechanics, The University of Western Australia, Australia*

## Abstract

*The variability in a rock mass must be considered in geotechnical engineering analyses and designs. Discrete fracture network (DFN) modelling accounts for structural variability in a rock mass, providing a valuable tool that may be used in various geotechnical applications.*

*DFNs provide a statistical representation of the rock mass discontinuity system by the stochastic generation of discontinuity sets. This is based on structural data collected in the field from boreholes or by mapping exposures. DFN generation therefore involves structural data collection from which discontinuity sets may be defined. Each discontinuity set within a single structural domain is characterised using statistical distributions to describe the orientation, spacing, and trace lengths of the discontinuities, which are used to provide input parameters for DFN generation. The quality of a DFN therefore relies on the quality of the field data and its interpretation.*

*This paper reviews the various approaches available to collect structural data for DFN generation. The advantages and limitations of each method is given, and data collection and analysis strategies are outlined.*

**Keywords:** *structural data collection, discrete fracture network modelling*

## 1 Introduction

In rock engineering design uncertainty and variability needs to be accounted for either implicitly or explicitly (Wesseloo & Joughin 2020). In many applications the variability within a rock mass has a significant influence on the design and needs to be quantified. One way of accounting for the variability of the rock mass discontinuity fabric is through the development of a discrete fracture network (DFN).

DFN modelling approaches are used in several applications in hydro-geological and geotechnical contexts in both underground and open pit environments, as is evident from the International Discrete Fracture Network Engineering conference series. Specific geomechanics applications include:

- Underground stability analyses (e.g. Esmaieli et al. 2010, 2013; Grenon & Hadjigeorgiou 2003; Grenon et al. 2015; Rogers et al. 2017).
- Open pit stability analyses (e.g. Montiel et al. 2020; Valerio et al. 2021; Weir & Fowler 2016).
- Ground support design (e.g. Hadjigeorgiou & Grenon 2017b).
- Numerical modelling (e.g. Esmaieli et al. 2010, 2013; Muaka et al. 2017; Vyazmensky 2008).
- Fragmentation assessments (e.g. Elmo et al. 2014; Rogers et al. 2010).

Vakili et al. (2014) defines a DFN as a stochastic representation of rock mass discontinuities that are simulated by computer code, based on the statistical distributions of discontinuity data gathered in the field.

In this paper we distinguish between a DFN model, and a DFN. Conceptually, a DFN model is a statistical model that captures the spatial variability of the discontinuity fabric of the rock mass. A DFN model is fully defined by a set of statistical input parameters and the fracture system model (e.g Baecher, Veneziano, refer to Staub et al. (2002) for a review of different models). With a single set of DFN input parameters, many different fracture networks can be generated. Each of these DFNs consist of a combination of discontinuities that satisfies the desired statistical parameters. Each DFN, therefore, is a different realisation of the DFN model satisfying the same statistical characteristics defined by that DFN model.

The purpose of the DFN model therefore, is to capture the variability of the discontinuities in a rock mass, leaving the designer to deal only with the uncertainty component. The way the designer deals with uncertainty is dependent on the scale of application and interpretation. For problems where the model is applied at a scale many times larger than the representative elementary volume (REV) it may be sufficient to perform analysis on only a few different DFNs, whilst for applications where the problem size is in the same order as the REV size, multiple analyses will need to be performed on multiple DFNs. This is the case for support design applications (Grenon et al. 2015, 2017; Hadjigeorgiou & Grenon 2017a). Conceptually, the REV is the smallest volume with behaviour representative of larger volumes. For more information on REV refer to (Esmaieli et al. 2010; Hudson & Harrison 1997; Schultz 1996).

The statistical distribution characteristics of large structures, like fault and shears, are distinctly different to the smaller scale structures, although related to it through a shared structural geological history. For the scale of application in mining, such large structures are excluded from the DFN model (excluded from the definition of 'fabric'). Where known larger scale deterministic structures from geological fault models exist, these may however, be input directly into a DFN (e.g. Weir et al. 2014).

DFN modelling requires structural data of a sufficient quality and quantity. Different discontinuity sets are defined and each discontinuity set is characterised by statistical distributions describing their orientation, spacing, and trace lengths. These parameter distributions provide information necessary to define and calibrate a DFN model. The quality of a DFN therefore relies heavily on the quality of the field data and its interpretation.

While the use of DFNs in some form or another is becoming more common and have many benefits, they are not routinely used by geotechnical practitioners. Reasons for this include a lack of understanding of key DFN input parameters and limited guidelines on how each parameter may be validated (Vakili et al. 2014) and calibrated. There is also uncertainty around structural data requirements and the data collection methods that may be adopted to acquire DFN parameters. In addition, traditional structural data collection methods such as scanline mapping and joint logging are time consuming and are thus not often employed at operating mine sites. This results in limited data being available for use in DFN generation.

In this paper, the common approaches available to collect structural data are reviewed. The advantages and limitations of each method for obtaining the required DFN input parameters are outlined and summarised. Data collection and data analysis strategies are also discussed.

# 2 DFN models

## 2.1 Fracture systems models

For the generation of a DFN, a spatial model that governs the way fractures will be generated within a given 3D volume is required. Examples of fracture spatial models include Baecher, Enhanced Baecher, nearest neighbour and Fractal Levy-Lee. A discussion of these models is outside the scope of this paper and the interested reader is referred to Staub et al. (2002) and Dershowitz and Einstein (1988). For the purpose of this paper we will limit our discussion with respect to the Baecher model (Baecher 1983) and its required input parameters.

DFNs are generated using input parameters derived from data characterised for separate discontinuity sets within a given structural domain. Input parameters for the Baecher model include fracture orientation, intensity, and size. These parameters are briefly described below.

### 2.1.1 Orientation

In geotechnical applications, the orientation of discontinuity data is defined by dip and dip direction. This information may be obtained from borehole data or by mapping exposures. Stereographic projections are routinely employed to visualise discontinuity data. Commercially available software facilitates the identification and definition of discontinuity sets, which may then be assigned to structural domains.

The distribution of the discontinuity orientation data is undertaken using the approach originally proposed by Fisher (1953) and summarised by Priest (1993), which provides a valuable model due to its simplicity and flexibility (Potvin & Hadjigeorgiou 2020). Priest (1993) notes however that it is a symmetric distribution, and consequently provides only an approximation for asymmetric data.

### 2.1.2 Intensity

Dershowitz & Herda (1992a) defined a system of fracture intensity measures of different dimensions applicable to a special joint set distribution. This is summarised and modified by Rogers et al. (2017) in Table 1. Fracture intensity measures are referred to as $P_{ij}$, where the subscript *i* refers to the dimensions of a sample and the subscript *j* refers to the dimension of measurement. An in depth discussion of the fracture intensity measures can be found in Dershowitz & Herda (1992a).

**Table 1 The $P_{ij}$ system of fracture intensity (modified after Rogers et al. 2017)**

| | | | **Dimension of measurement** | | | |
|---|---|---|---|---|---|---|
| | | | **0**<br>**Count** | **1**<br>**Length (m)** | **2**<br>**Area ($m^2$)** | **3**<br>**Volume ($m^3$)** |
| Dimension of sample | 1 | Length (m) | $P_{10}$ ($m^{-1}$)<br>No. of fractures per length | $P_{11}$ ($m^{-1}$)<br>Length of fracture traces per length | | |
| | 2 | Area ($m^{-2}$) | $P_{20}$ ($m^{-2}$)<br>No. of fractures per area | $P_{21}$ ($m^{-1}$)<br>Length of fracture traces per area | | |
| | 3 | Volume ($m^{-3}$) | $P_{30}$ ($m^{-3}$)<br>No. of fractures per volume | | $P_{32}$ ($m^{-1}$)<br>Area of fractures per volume | $P_{33}$ ( – ) volume of fractures per volume |

The preferred method of fracture intensity for the generation of a DFN is $P_{32}$ (fracture area/unit volume) (Rogers et al. 2017). $P_{32}$ is an intrinsic property of the rock mass and cannot be measured in situ (Weir & Fowler 2016). $P_{32}$ can be estimated by multiplying $P_{10}$ and $P_{21}$ with conversion factors (Dershowitz & Herda 1992b; Wang 2005). Since the value of $P_{32}$ cannot be measured directly it needs to be calibrated after initial estimation.

It is important to note that the intensity measure $P_{32}$ is independent of the size of the fracture set. A fracture set with large persistence and larger spacing can have the same fracture intensity parameter $P_{32}$ than a set with smaller spacing and shorter persistence. To correctly characterise the fracture network, the size distribution of fractures must also be defined.

#### *2.1.3 Size*

Fracture size is typically the most difficult parameter to quantify since it cannot be directly measured. The Baecher model assumes the fractures to be circular and requires a mean fracture diameter per discontinuity set as an input to quantify persistence. Statistical fracture size measures are estimated and calibrated against trace length data, which act as a footprint for 3D discontinuities as they intersect sampling planes.

Trace length may be defined as “the length of a fracture trace formed as the intersection between a fracture and 2-d sampling line” (Mauldon & Dershowitz 2000). This is a difficult property to measure, as there is limited exposure in underground excavations. Furthermore, trace length cannot be derived from borehole data, due to the small diameters of the core (usually <63 mm). Trace length is subjected to four major biases due to sampling errors. These include orientation bias, size bias, truncation bias, and censoring bias. These should be corrected when estimating the mean trace length for an infinite surface. This may be achieved by applying the analytical solution provided by Zhang & Einstein (1998).

# 3 Structural data collection

Structural data collection is essential to characterise structures and provide the input parameters necessary to achieve a calibrated DFN. The two basic approaches to collect structural data are via borehole core and by mapping exposures. Borehole data collection methods are structural logging and the use of geophysical in hole tools. Mapping includes traditional approaches (scanline and window mapping) and the use of digital techniques (photogrammetry and light detection and ranging (LiDAR) scans). These approaches are described and discussed below.

## 3.1 Data collection from boreholes

In the early stages of a project when rock exposures are not available, structural logging is generally undertaken. Geophysical methods may also be adopted at this stage.

#### *3.1.1 Structural/joint logging*

As described by Potvin & Hadjigeorgiou (2020), structural logging focuses on characterising and obtaining orientation data for every discontinuity intersecting the core. In this method, inclined boreholes are used, and orientation techniques are employed to mark a reference/orientation line on the core (Figure 1).

**Figure 1 Orientation line marked on borehole core**

Discontinuities present in the core are measured in the form of alpha and beta angles from which dip and dip direction may be calculated, based on the orientation line and orientation of the borehole. The alpha angle is defined as the acute angle measured from the core axis to the tip of the discontinuity (Potvin & Hadjigeorgiou 2020). The beta angle is a circumferential measurement typically taken from the orientation line to the tip of the joint (Figures 2a and 2b). It is important to note that the way the beta measurement is taken can vary for different mine sites. This is illustrated in Figures 2c and 2d, where the beta measurement is taken from the tip of the joint to the orientation line, in either a clockwise or counter clockwise direction. Due to the variations in the way the beta angle may be measured, it is critical to note the beta measurement method during the logging process, to ensure that this is accounted for in the dip and dip direction calculations correctly.

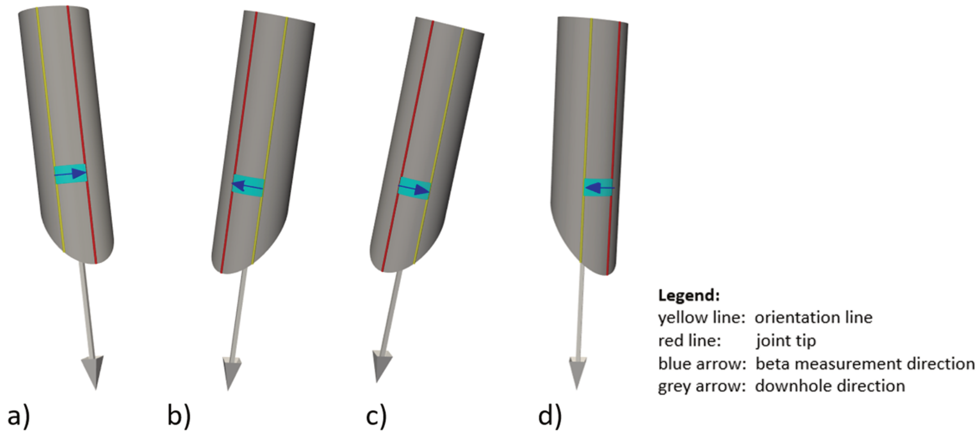



**Figure 2 Beta measurements methods. (a) Counter clockwise measurement from orientation line to joint tip; (b) Clockwise measurement from orientation line to joint tip; (c) Clockwise measurement from joint tip to orientation line; (d) Counter clockwise measurement from joint tip to orientation line**

Overall good orientation data can be achieved from structural logging provided that:

- The orientation line is reliable.
- The beta measurement method is accounted for correctly in the dip and dip direction calculations.

For the purposes of achieving DFN input parameters, in addition to orientation data, fracture intensity ($P_{10}$) may also be captured, provided that every discontinuity is measured. As mentioned above, trace length information cannot be captured from borehole core.

The advantages and limitations of structural logging is summarised in Table 2.

**Table 2 Advantages and limitations of structural logging**

| Advantages | Limitations |
|---|---|
| Good orientation data may be achieved, (provided that the orientation line quality is reliable, and the beta measurement method is accounted for corrected). | Can provide incorrect orientation results if the way in which the beta angle is measured is not communicated well or is inconsistent. |
| Fracture intensity ($P_{10}$) may be determined. | Orientated core is required. This is slower and more costly. |
| Small-scale roughness can be obtained. | Large-scale roughness cannot be logged. |
| Joint infill properties can be obtained. | Trace length cannot be logged. |
| | Time consuming. |

Overall, structural logging is a time-consuming approach, which often results in the employment of geophysical methods to supplement this data.

### *3.1.2 Geophysical methods*

Acoustic and optical televiewers (TV) are routinely used in boreholes to capture structural data. These tools provide rapid and accurate high-resolution oriented images of the borehole walls (Figure 3). In this method the picking of structures is carried out by the televiewer operator, who then provides this data to geotechnical practitioners (Gwynn et al. 2013). As this is less time consuming than structural logging, this method is often used as a replacement or in addition to the structural logging of borehole core.

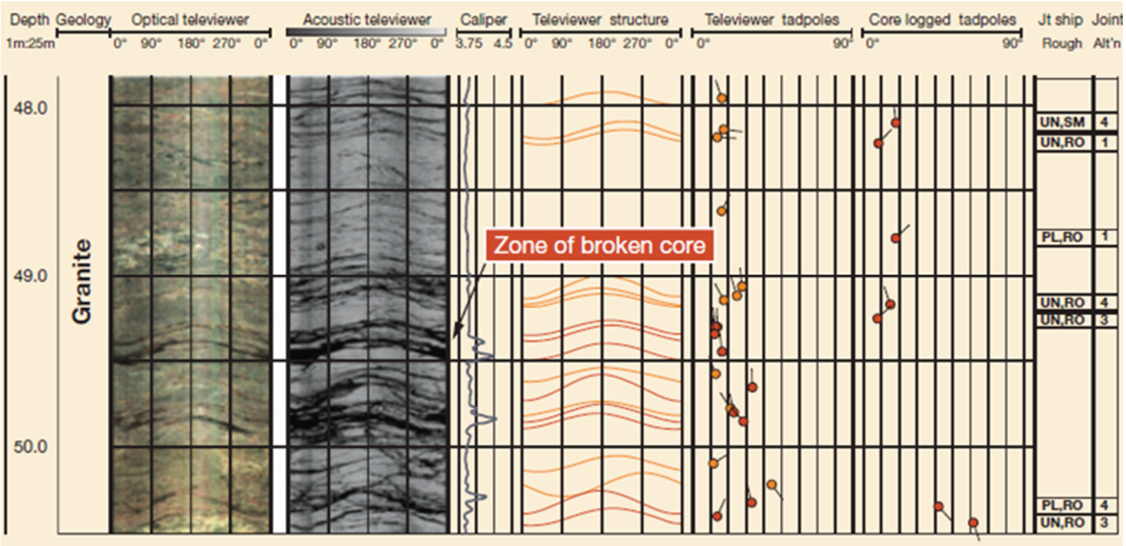



**Figure 3 Optical and acoustic televiewer images (Potvin & Hadjigeorgiou 2020)**

General comments on televiewer logging is summarised by Gwynn et al. (2013) as follows:

- TV logging should be undertaken as soon as the borehole has been completed, to reduce the risk of borehole collapse.
- It is essential that the individual(s) tasked with picking structures has a good understanding of the survey process and associated software. Adequate training to confidently use the TV logging software is therefore required.
- Core spin can cause a horizontal artefact on the borehole wall. This is picked up by the TV and may be mistaken for or can mask horizontal discontinuities. This can, however, be verified on the inspection of the core.

In terms of achieving DFN input parameters, good orientation data may be obtained. Fracture intensity ($P_{10}$) can also be captured, provided that every discontinuity is recorded. As with structural logging, large-scale roughness and trace length information cannot be captured due to the small diameter of borehole core. Joint strength characteristics (i.e. small-scale roughness and joint infill) also cannot be determined from this method; however this is not directly required for the generation of a DFN.

The advantages and limitations of the use of geophysical methods is summarised in Table 3.

**Table 3 Advantages and limitations of geophysical methods**

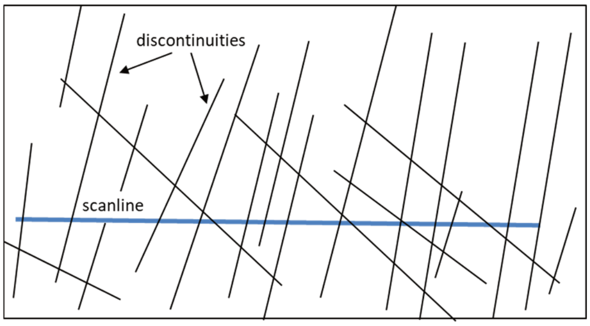
| Advantages | Limitations |
|---|---|
| Good orientation data may be achieved. | Core spin may mask or be mistaken for horizontal discontinuities. |
| Fracture intensity ($P_{10}$) may be captured. | Roughness cannot be logged. |
| Less time consuming than structural logging. | Trace length cannot be logged. |
| | Should be undertaken as soon as the borehole has been completed, to reduce the risk of borehole collapse. |

## 3.2 Traditional mapping approaches

Once mining commences and rock exposures become available, mapping may be carried out. The traditional approaches to mapping are line mapping and window mapping (International Society for Rock Mechanics (ISRM) 1978a). With the advances in technology, photogrammetry, and LiDAR scans have also become available.

### *3.2.1 Scanline mapping*

Scanline mapping is a systematic, unidimensional approach that involves the use of a scanline tape (Priest 1993). The tape is positioned in a straight line along an excavation surface (Figure 4). A detailed record is then made for each discontinuity that cuts through the scanline tape. Similar to boreholes, scanline mapping is a one-dimensional sampling technique. Information, not available from borehole data is the trace length, providing essential data for DFN model development and calibration. In addition to orientation data and trace length, fracture intensity parameters $P_{10}$ and $P_{11}$ can also be obtained.



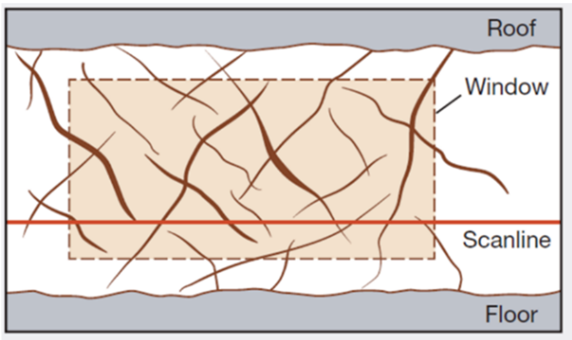

(a)

(b)

**Figure 4 Scanline mapping. (a) Illustration; (b) Underground**

### *3.2.2 Window mapping*

Window mapping is a method of systematically mapping discontinuities inside a window of a fixed size (Figure 5). In this method, the measurement techniques are essentially the same as for scanline sampling, except that all discontinuities within a defined area of the rock face are measured, rather than only those that intersect the scanline (Priest 1993). In addition to data obtained from scanline mapping, one can also obtain data intensity parameters $P_{20}$ and $P_{21}$. Further information necessary for more complex fracture systems models (hierarchical model) are termination statistics.




(a)

(b)

**Figure 5 (a) Window mapping illustration (Potvin & Hadjigeorgiou 2020); (b) Window mapping on a surface exposure**

### *3.2.3 Advantages and limitations of scanline and window mapping*

A clear advantage of scanline and window mapping over borehole logging techniques is that trace length information and large-scale roughness can be obtained. In addition to this, an overall impression of the rock mass conditions may be formed, due to a larger proportion of rock being exposed.

Given that both methods require every discontinuity to be manually recorded, these methods are limited in that they are time consuming. These approaches are also difficult to apply in highly fractured ground, where there are too many discontinuities to systematically map. While this is the case, scanline and window mapping offer the opportunity to collect valuable structural data and provide all that is required to achieve the above-mentioned DFN input parameters. This is attained in the following way:

- Dip and dip direction is recorded directly with the use of a compass or a similar instrument, providing orientation data.
- As there is an exposure present, trace length information can be collected.
- Every discontinuity should be recorded , therefore the number of fractures per unit length ($P_{10}$) and the length of fractures intersected by the scanline ($P_{11}$) can be determined for scanline mapping. $P_{20}$ (i.e. number of fracture per area) and $P_{21}$ (i.e. the trace length per unit of mapped area) can be obtained from window mapping.

A summary of the advantages and limitations of scanline and window mapping is given in Table 4.

**Table 4 Advantages and limitations of scanline and window mapping**

| Advantages | Limitations |
|---|---|
| Overall impression of rock mass conditions. | Time consuming. |
| Allows for the collection of trace length data. | Difficult to apply in highly complex rock masses. |
| Joint strength properties can be collected. | |
| Large-scale joint roughness can be collected. | |
| Joint orientation (dip and dip direction) can be obtained. | |
| Fracture intensity may be determined:<br>• $P_{10}$ and $P_{11}$ from scanline mapping.<br>• $P_{20}$ and $P_{21}$ from window mapping. | |

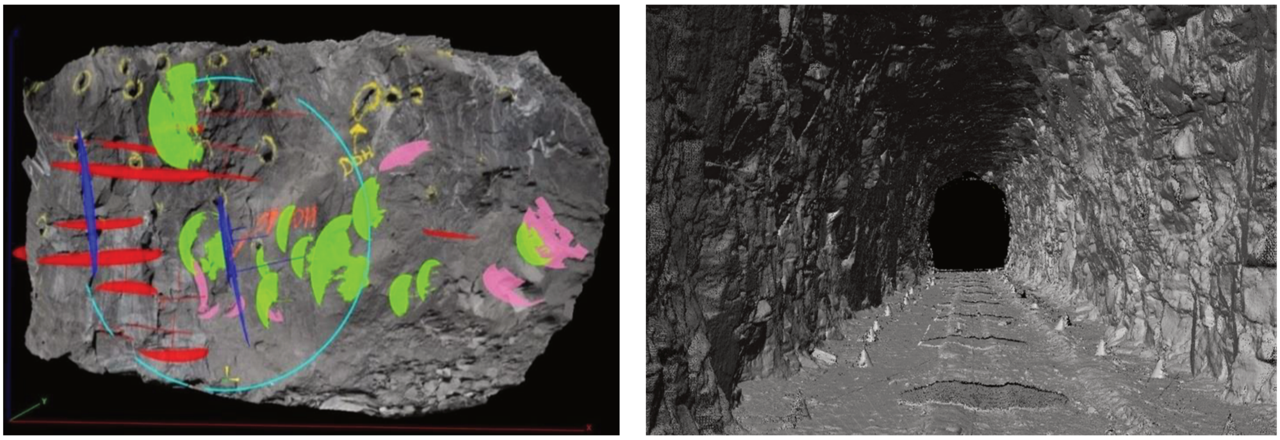
## 3.3 Digital mapping techniques

With advances in technology, digital mapping using photogrammetry and LiDAR scans has become available to obtain structural data.

3D photogrammetry involves the processing of stereo pairs of photographs to generate 3D images (Figure 6a). Structural data is gained by the interpretation of the 3D images using commercially available software such as Sirovision, ShapeMetriX3D, and the 3DM Analyst Mine Mapping Suite.

LiDAR scanning uses a transmitted and reflected laser beam to record millions of highly accurate points in space (Vazaios et al. 2017). This is done to create a 3D image of the scanner's surroundings (Figure 6b). The points are defined in a 3D coordinate system relative to the scanner and are known as point clouds. The virtual geometry formed by these dense point clouds allows the engineer to perform, on a computer, many geotechnical analysis tasks normally requiring sustained human access to the rock face (Fekete & Diederichs

2013). Discontinuity orientation measurements can be made semi-automatically (Feng & Röshoff 2015) or automatically (Slob et al. 2005) in the 3D surface model.



(a) (b)

**Figure 6 (a) 3D face model with major discontinuity sets mapped using a 2 m radius mapping window (Grenon et al. 2015); (b) 3D image in perspective created from the point clouds of 13 consecutive scans (Vazaios et al. 2017)**

### *3.3.1 Advantages and limitations of digital mapping techniques*

Several authors discuss the advantages and limitations of digital mapping compared with manual discontinuity sampling methods (e.g. Birch 2006; Fekete & Diederichs 2013; Sturzenegger & Stead 2009).

Advantages of digital mapping include:

- Reduction of time and effort required for mapping.
- Safety of the engineer or geologist performing the mapping.
- Greater quantity of collected data, allowing more appropriate application of statistical tools.
- Reduced bias in the measurement selection.
- Easier access to various regions of exposures.
- Increased accuracy of measurements.
- Measurements are not influenced by magnetic rock.

An inherent limitation of digital mapping techniques is that it cannot adequately capture discontinuity strength characteristics (i.e. joint roughness and joint infill). In addition, Potvin & Hadjigeorgiou (2020) indicate that analysis is hindered by the presence of surface support (i.e. mesh and shotcrete). In underground mines, photogrammetry also requires an external light source. As LiDAR is not subjected to this limitation, Vazaios et al. (2017) argues that this approach is more suitable to the underground environment.

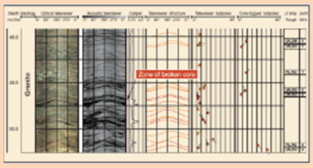
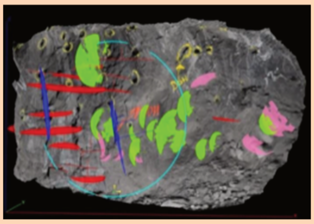
Overall, both photogrammetry and LiDAR scans allow for orientation, fracture intensity ($P_{20}$ and $P_{21}$) and trace length information to be obtained, which may be used to define DFN input parameters. As with window mapping, it is important that LiDAR and photogrammetry data encompasses all fractures for a given area, to enable one to obtain accurate intensity parameter estimates as well as representative size distributions for discontinuity sets.

Examples where photogrammetry has been used to produce DFNs for geotechnical applications may be found in work carried out by (Grenon et al. 2015, 2017) and (Rogers et al. 2017). An example where LiDAR data has been used for the determination of DFN input parameters is given by Vazaios et al. (2017).

## 3.4 Summary of structural data collection methods for DFN modelling

A summary of the structural data collection methods for establishing DFN input parameters is given in Table 5.

**Table 5 Summary of structural data collection methods for establishing DFN input parameters**

| **Data collection method** | **Likely data volumes** | **DFN model inputs** | | |
|---|---|---|---|---|
| | | **Orientation** | **Intensity** | **Size** |
| Structural core logging<br> | Large | ✓ (Alpha and beta) | $P_{10}$ | × |
| Geophysical methods<br> | Large | ✓ | $P_{10}$ | × |
| Photogrammetry<br> | Medium | ✓ (Digital) | $P_{10}$, $P_{11}$, $P_{20}$, $P_{21}$ | ✓ |
| LiDAR scans<br> | Medium | ✓ (Digital) | $P_{10}$, $P_{11}$, $P_{20}$, $P_{21}$ | ✓ |
| Line mapping<br> | Small | ✓ | $P_{10}$, $P_{11}$ | ✓ |
| Window mapping<br> | Small | ✓ | $P_{10}$, $P_{11}$, $P_{20}$, $P_{21}$ | ✓ |

# 4 Data collection and analysis strategies for DFN modelling

Due to the nature of the different data collection methods, a mine site structural dataset is likely to contain structural logging data and televiewer data and little, if any, line mapping and window mapping data. The digital nature of photogrammetry and LiDAR approaches allow for easier structural data collection and if this forms part of the data gathering campaign, can result in a significant contribution to the dataset.

For the purpose of developing a DFN, data obtained from boreholes can result in sufficient quantity and quality of orientation data, enabling one to define discontinuity sets for different structural domains. This data is also available at the early stages of a project. This data is, however, insufficient for the generation of a DFN, as it lacks persistence data and higher order intensity data. Dominant drilling directions may also result in orientation biases.

Borehole-based data must, therefore, be supplemented with data from exposures. Where underground mines are developed below an open pit, the open pit provides large exposures and the opportunity to gather valuable joint size data, lacking from borehole data.

Underground mapping will also be necessary to ensure sufficient spatial covering in all structural domains. In addition, data should also be collected in different directions to minimise orientation biases. A detailed discussion on structural data biases can be found in Fowler (2013).

Scanline mapping provides a systematic data collection method that can be performed with limited training. The data obtained from a scanline, is simply a sub-set of that obtained from window mapping, LiDAR, and photogrammetry approaches, if all fractures within the designated area are measured. One can, for example, extract scanline data from window mapping data by sub-sampling the mapped joints along a line positioned on the window. Considering the labour-intensive nature of scanline and window mapping, LiDAR/Photogrammetry are more productive methods for supplementing borehole-based data for the purpose of DFN generation. Where digital mapping is adopted, all discontinuities (above a lower cut-off size threshold) within the mapping area must be recorded. This is to obtain reliable intensity and size data.

Scanline and window mapping is still required for obtaining joint strength properties for different discontinuity sets. This is important data used in mechanical analyses but is not required to develop a DFN.

For improved efficiency in structural data gathering for the purpose of DFN generation, the following approach is suggested:

- Define discontinuity sets and structural domains from available borehole-based orientation data.
- Flag possible blind spots due to orientation biases.
- Supplement borehole data with targeted LiDAR/photogrammetry approaches to:
  - Reduce orientation biases.
  - Collect sufficient data to define the size distribution for each discontinuity set.
- Where it is not possible to adopt digital mapping approaches, traditional mapping techniques may be utilised. As these are time-consuming approaches, paperless options that improve the efficiency of these methods are becoming available. An example of this is the Data Collection browser-app by mXrap (Harris & Wesseloo 2015). This browser-app aids the collection of discontinuity data for scanlines and contains several built-in tools that significantly improve the efficiency of the method.

There are no well accepted guidelines for number of discontinuity data points to collect, however approximately 80 to 300 discontinuities per set is generally accepted (ISRM 1978b; Priest 1993) as sufficient to statistically define the orientation, and persistence properties of a discontinuity set. It is assumed that this guideline will suffice to provide the data required to produce a DFN.

As DFNs are created per structural domain, the following analysis and domaining strategies are advised:

- Major structures and lithological contacts may act as structural domain boundaries and therefore serve as a good starting point for boundary definition.
- Attention should be given to the orientations of major structures, as discontinuity sets often occur at similar orientations to major structures.
- To achieve structural domains, one approach is the analysis of discontinuity data for smaller areas at first. Stereonets may be created, and sets may be identified in these areas. Similarities between each area may result in combining data from these areas together or separating them into different domains.
- Where possible, identified discontinuity sets should be verified underground.
- Generally, data points with a trace length of less than 1 m may be excluded from analyses, as these data points often represent blast damage.

Calibrated DFN models require discontinuity data of a sufficient quantity and quality, which include orientation, intensity, and size information. The gathering of this data is time consuming and labour intensive, especially for intensity and size. Currently this seems to be an important hurdle for the use of DFN modelling in the mining industry. The application of machine learning techniques has proven extremely valuable in many applications and its application is already pursued to automatically identify fractures from photogrammetry, LiDAR and downhole geophysics. We see the application and further development of machine learning techniques in the gathering of structural data as a crucial component in the development of DFN technology and its use in the mining industry.

# 5 Conclusion

DFNs account for structural variability in a rock mass, providing a valuable tool that may be used in various geotechnical applications. These include support designs, stability analyses, numerical modelling, and fragmentation assessments.

While the use of DFNs is becoming more common and have many benefits, they are not routinely used by geotechnical practitioners. This is partly due to uncertainty around structural data requirements and the data collection methods that may be adopted to acquire DFN parameters.

This paper reviewed the common methods available to collect structural data for the purpose of producing a DFN. The two basic approaches are via borehole core and by mapping exposures. Borehole data collection methods are structural logging and the use of geophysical in hole tools. Mapping includes traditional approaches (scanline and window mapping) and the use of digital techniques (LiDAR and photogrammetry).

Mining structural databases generally contain orientation data of sufficient quality and quantity, but often lack sufficient size and intensity data, which is a critical component of a calibrated DFN model. Due to the time-consuming and labour-intensive nature of scanline and window mapping, as well as the lack of convenient access to exposures, these methods are not widely used.

Photogrammetry and LiDAR scanning techniques provide a more convenient and efficient approach to gathering size and intensity data. These methods, however, are often used for spot mapping of discontinuities. For the generation of a DFN, all discontinuities (above a lower cut-off size threshold) within a mapping area must be recorded to obtain reliable intensity and size data.

The further application and development of machine learning techniques in the gathering of structural data is a crucial component in the development of DFN technology and its use in the mining industry.

In addition to the use of suitable data collection methods, appropriate data collection and data analysis strategies should be adopted, to adequately provide DFN input parameters. After the initial determination of DFN input parameters, DFN calibration must also be carried out to ensure that the DFN represents the data collected in the field as closely as possible. Once calibrated, a DFN may be used in geotechnical applications.

## Acknowledgement

This work was funded by the Ground Support Systems Optimisation Phase 2 research project at the Australian Centre for Geomechanics, The University of Western Australia. Project sponsors were Agnico Eagle, LaRonde mine; BHP, Olympic Dam mine; DSI Underground; Epiroc, New Concept Mining; Fero Strata Australia (now DSI Underground); Garock Pty Ltd; Gold Fields Australia Pty Ltd; IGO Limited; IAMGOLD Corporation, Westwood mine; Jennmar Australia; Minerals Research Institute of Western Australia (MRIWA); Newcrest Mining Limited, Cadia Valley Operations; Sandvik Australia Pty Ltd.

## References

Baecher, G 1983, 'Statistical analysis of rock mass fracturing', *Mathematical Geology*, vol. 15, no. 2, pp. 329–348.

Birch, J 2006, 'Using 3DM Analyst mine mapping suite for rock face characterization', *Laser and Photogrammetric Methods for Rock Face Characterization*, vol. 15.

Dershowitz, WS & Einstein, HH 1988, 'Characterizing rock joint geometry with joint system models', *Rock Mechanics and Rock Engineering*, vol. 21, no. 1, pp. 21–51, doi.org/10.1007/bf01019674

Dershowitz, WS & Herda, HH 1992a, 'Interpretation of fracture spacing and intensity', in JR Tillerson & WR Wawersik (eds), *Proceedings of the 33rd U.S. Symposium on Rock Mechanics*, A.A. Balkema, Rotterdam.

Dershowitz, WS & Herda, HH 1992b, 'Interpretation of fracture spacing and intensity', in JR Tillerson & WR Wawersik (eds), *Proceedings of The 33rd U.S. Symposium on Rock Mechanics*, A.A. Balkema, Rotterdam.

Elmo, D, Liu, Y & Rogers, S 2014, 'Principles of discrete fracture network modelling for geotechnical applications', *Proceedings of the First International DFNE Conference*.

Esmaieli, K, Hadjigeorgiou, J & Grenon, M 2010, 'Estimating geometrical and mechanical REV based on synthetic rock mass models at Brunswick Mine', *International Journal of Rock Mechanics and Mining Sciences*, vol. 47, no. 6, pp. 915–926, doi.org/10.1016/j.ijrmms.2010.05.010

Esmaieli, K, Hadjigeorgiou, J & Grenon, M 2013, 'Stability analysis of the 19A ore pass at Brunswick mine using a two-stage numerical modeling approach', *Rock Mechanics and Rock Engineering*, vol. 46, no. 6, pp. 1323–1338.

Fekete, S & Diederichs, M 2013, 'Integration of three-dimensional laser scanning with discontinuum modelling for stability analysis of tunnels in blocky rockmasses', *International Journal of Rock Mechanics and Mining Sciences*, vol. 57, pp. 11–23, doi.org/10.1016/j.ijrmms.2012.08.003

Feng, Q & Röshoff, K 2015, 'A survey of 3D laser scanning techniques for application to rock mechanics and rock engineering', in R Ulusay (ed), *The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007-2014*, Springer International Publishing, Cham, pp. 265–293.

Fisher, RA 1953, 'Dispersion on a sphere', *Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences*, vol. 217, no. 1130, pp. 295–305.

Fowler, MJ 2013, 'Structural data bias in the digital age', in PM Dight (ed.), *Slope Stability 2013: Proceedings of the 2013 International Symposium on Slope Stability in Open Pit Mining and Civil Engineering*, Australian Centre for Geomechanics, pp. 219–225, 10.36487/ACG_rep/1308_09_Fowler

Grenon, M & Hadjigeorgiou, J 2003, 'Drift reinforcement design based on discontinuity network modelling', *International Journal of Rock Mechanics and Mining Sciences*, vol. 40, no. 6, pp. 833–845, doi.org/10.1016/S1365-1609(03)00044-3

Grenon, M, Landry, A, Hadjigeorgiou, J & Lajoie, PL 2015, 'Contribution to drift design using discrete fracture network modelling at the Éléonore Mine in Canada', in Y Potvin (ed.), *Design Methods 2015: Proceedings of the International Seminar on Design Methods in Underground Mining, Australian Centre for Geomechanics*, Perth, pp. 339–350, doi.org/10.36487/ACG_rep/1511_20_Grenon

Grenon, M, Landry, A, Hadjigeorgiou, J & Lajoie, PL 2017, 'Discrete fracture network based drift stability at the Éléonore mine', *Mining Technology*, vol. 126, no. 1, pp. 22–33, doi.org/10.1080/14749009.2016.1199296

Gwynn, XP, Brown, MC & Mohr, PJ 2013, 'Combined use of traditional core logging and televiewer imaging for practical geotechnical data collection', in PM Dight (ed.), *Slope Stability 2013: Proceedings of the 2013 International Symposium on Slope Stability in Open Pit Mining and Civil Engineering*, Australian Centre for Geomechanics, Perth, pp. 261–272, doi.org/10.36487/ACG_rep/1308_13_Mohr

Hadjigeorgiou, J & Grenon, M 2017a, 'Drift reinforcement design based on Discrete Fracture Network (DFN) modeling', in X-T Feng (ed.), *Rock Mechanics and Engineering*, CRC Press, Boca Raton.

Hadjigeorgiou, J & Grenon, M 2017b, *Drift Reinforcement Design Based on Discrete Fracture Network (DFN) Modelling*, Taylor & Francis Group, Miton Park, pp. 123–146.

Harris, P & Wesseloo, J 2015, *mXrap*, version 5, computer software, Australian Centre for Geomechanics, The University of Western Australia, Perth, mxrap.com

Hudson, JA & Harrison, JP 1997*, Engineering Rock Mechanics*, Elsevier, Oxford.

ISRM 1978a, 'International society for rock mechanics commission on standardization of laboratory and field tests: Suggested methods for the quantitative description of discontinuities in rock masses', *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, vol. 15, no. 6, pp. 319–368, doi.org/10.1016/0148-9062(78)91472-9

ISRM 1978b, 'Suggested methods for the quantitative description of discontinuities in rock masses', *International Journal of Rock Mechanics and Mining*, vol. 15, pp. 89–97.

Mauldon, M & Dershowitz, W 2000, 'A multi-dimensional system of fracture abundance measures', *Geological Society of America Abstracts with Programs*, pp. A474.

Montiel, E, Varona, P, Fernandez, C & Espinoza, Z 2020, 'Use of discrete fracture networks in 3D numerical modelling for stability analysis in open pits', in PM Dight (ed.), *Slope Stability 2020: Proceedings of the 2020 International Symposium on Slope Stability in Open Pit Mining and Civil Engineering*, Australian Centre for Geomechanics, Perth, pp. 913–926, doi.org/10.36487/ACG_repo/2025_60

Muaka, JJM, Duma, S, Mushangwe, P, Gardner, L, Chindedza, T, Walls, J & Joughin, WC 2017, 'Modelling hard rock jointed pillars using a distinct element and discrete fracture network approach considering the effect of a clay-filled shear structure', *Proceedings of the Eighth International Conference on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, 10.36487/ACG_rep/1704_22_Muaka

Potvin, Y & Hadjigeorgiou, J 2020, *Ground Support for underground mines*, Australian Centre for Geomechanics, Perth.

Priest, SD 1993, *Discontinuity Analysis for Rock Engineering*, Chapman and Hall, London.

Rogers, S, Elmo, D, Webb, G & Catalan, A 2010, 'A discrete fracture network based approach to defining in situ, primary and secondary fragmentation distributions for the Cadia East panel cave project', in Y Potvin (ed.), *Caving 2010: Proceedings of the Second International Symposium on Block and Sublevel Caving*, Australian Centre for Geomechanics, Perth, pp. 425–439, 10.36487/ACG_rep/1002_29_Rogers

Rogers, SF, Bewick, RP, Brzovic, A & Gaudreau, D 2017, 'Integrating photogrammetry and discrete fracture network modelling for improved conditional simulation of underground wedge stability', in J Wesseloo (ed.), *Deep Mining 2017: Proceedings of the Eighth International Conference on Deep and High Stress Mining*, Australian Centre for Geomechanics, Perth, pp. 599–610, doi.org/10.36487/ACG_rep/1704_40_Rogers

Schultz, RA 1996, 'Relative scale and the strength and deformability of rock masses', *Journal of Structural Geology*, vol. 18, no. 9, pp. 1139–1149, doi.org/10.1016/0191-8141(96)00045-4

Slob, S, van Knapen, B, Hack, R, Turner, K & Kemeny, J 2005, 'Method for automated discontinuity analysis of rock slopes with three-dimensional laser scanning', *Transportation Research Record*, vol. 1913, no. 1, pp. 187–194, doi.org/10.1177/0361198105191300118

Staub, I, Fredriksson, A & Outters, N 2002, *Strategy for a Rock Mechanics Site Descriptive Model Development and Testing of the Theoretical Approach*, Svensk Kärnbränslehantering AB, Sweden.

Sturzenegger, M & Stead, D 2009, 'Close-range terrestrial digital photogrammetry and terrestrial laser scanning for discontinuity characterization on rock cuts', *Engineering Geology*, vol. 106, no. 3, pp. 163–182, doi.org/10.1016/j.enggeo.2009.03.004

Vakili, A, Teet, R, Woo, K-S, de Veth, A & Penney, AR 2014, 'Understanding critical parameters in stochastic discrete fracture networks', *Proceedings of The First International Conference on Discrete Fracture Network Engineering*.

Valerio, M, Rogers, S, Lawrence, KP, Byrne, C, Veltin, K, Darakijan, T, Gaida, M, Cambio, D & Chapin, GK 2021, 'Improving bench design through discrete fracture network analysis', in PM Dight (ed.), *SSIM 2021: Second International Slope Stability in Mining*, Australian Centre for Geomechanics, Perth, pp. 457–472, doi.org/10.36487/ACG_repo/2135_29

Vazaios, I, Vlachopoulos, N & Diederichs, MS 2017, 'Integration of lidar-based structural input and discrete fracture network generation for underground applications', *Geotechnical and Geological Engineering*, vol. 35, no. 5, pp. 2227–2251, doi.org/10.1007/s10706-017-0240-x

Vyazmensky, A 2008, *Numerical Modelling of Surface Subsidence Associated with Block Cave Mining Using a Finite Element/Discrete Element Approach*, PowerPoint presentation, dx.doi.org/10.13140/RG.2.1.4069.3843

Wang, X 2005, *Stereological Interpretation of Rock Fracture Traces on Borehole Walls and Other Cylindrical Surfaces*, PhD thesis, Virginia Tech, Blacksburg.

Weir, F, de Ambrosis, A & Fowler, M 2014, 'Discrete fracture network modelling for tunnel design in the Sydney Basin', *Proceedings of the 15th Australasian Tunnelling Conference*, Australasian Institute of Mining and Metallurgy, Melbourne, pp. 219–228.

Weir, FM & Fowler, MJ 2016, 'Discrete fracture network modelling for hard rock slopes', in PM Dight (ed.), *APSSIM 2016: Proceedings of the First Asia Pacific Slope Stability in Mining Conference*, Australian Centre for Geomechanics, Perth, pp. 157–168, doi.org/10.36487/ACG_rep/1604_06_Weir

Wesseloo, J & Joughin, WC 2020, 'Probability, risk and design', in Y Potvin & J Hadjigeorgiou (eds), *Ground Support for underground mines*, Australian Centre for Geomechanics, Perth. pp. 377–396.

Zhang, L & Einstein, HH 1998, 'Estimating the mean trace length of rock discontinuities', *Rock Mechanics and Rock Engineering*, vol. 31, no. 4, pp. 217–235, doi.org/10.1007/s006030050022