# RELIABILITY ANALYSIS OF DISCRETE FRACTURE NETWORK PROJECTIONS FROM BOREHOLE TO SHAFT SCALE DISCONTINUITY DATA

by

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#### Abstract

When listing the risk factors that may impact the feasibility and success of a block cave operation, Brown (2003) highlights the adequacy of the geotechnical data available as a primary risk. Detailed data on the major structures, rock mass properties, and in situ stresses are necessary to assess the caveability of the orebody, and the excavation stability on the operating levels below, including the potential for fault slip and rockburst hazards when mining in a higher stress environment. The source of this essential data, especially at feasibility-level design, is almost always limited to borehole data. This is emphasized by Laubscher (2000) who notes that most block cave mines are designed solely on borehole data.

When restricted to borehole data, significant effort is expended on obtaining oriented core and/or televiewer logs to derive critical data regarding the frequency and orientation of discontinuities and the presence of major faults. Subsequent analysis of the spatial relationships between discontinuities is facilitated by the use of Discrete Fracture Network (DFN) modelling. The value of DFN models for assessing in situ fragmentation and rock mass strength identifies a critical limitation of borehole data. Required DFN inputs include the orientation, intensity, and size distributions of the discontinuities to allow the stochastic generation of a representative fracture network. The evaluation of the discontinuity orientation is relatively easy, intensity or spacing is possible with sufficient effort, but the discontinuity size is not possible given the small "observation window" of a borehole.

This thesis reports the results from research carried out to compare analyses of discontinuity data sampled across different spatial scales to improve our understanding and reduce uncertainty in the characterization and projection of discontinuity networks, specifically with respect to fracture spacing and persistence within the rock mass. This work is undertaken using discontinuity data from a deep geotechnical borehole and co-located large diameter shaft. The close proximity of the borehole and shaft provided an opportunity to ground-truth borehole projections based on traditional core logging and televiewer logs. The comparative analysis of discontinuities was completed with the use of DFN modelling. The improved understanding of the spacing and persistence of the discontinuities will aid in further development of guidelines for rapid geotechnical characterization.

# Preface

This thesis is original work by the author, Christina Brueckman. The work presented discusses the application of stochastic modeling, discrete fracture network (DFN) engineering, and the result of computer simulations, model calibration and validation. Real case studies are included as part of the analysis and procedures developed.

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# List of Abbreviations

| CEMI    | Centre for Excellence in Mining Innovation                |
|---------|---|
| cm      | centimeter  |
| FPI     | full perimeter intersection                               |
| FPC     | full perimeter criteria                                   |
| EFPC    | extended full perimeter criteria                          |
| DFN     | Discrete Fracture Network                                 |
| GSI     | Geological Strength Index                                 |
| ISIS    | Interactive Set Identification System                     |
| М       | Richter Magnitude   |
| m       | meter   |
| mm      | millimeter  |
| MRMR    | Modified Rock Mass Rating                                 |
| RCC     | Resolution Copper Company                                 |
| RMR     | Rock Mass Rating  |
| RTC-UMC | Rio Tinto Centre for Underground Mine Construction Centre |
| RQD     | Rock Quality Designation                                  |
| Q       | Rock Tunneling Quality Index                              |
| tpd     | tonnes per day  |
| UCS     | Uniaxial Compressive Strength                             |

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# Dedication

To my brothers, Rafe and Cody, for the unconditional love, encouragement, and support.

## **Chapter 1: Introduction**

The investigation and geotechnical characterization of a site is a critical step towards the design of any mining or civil construction project. For underground works, detailed data on the intermediate and major size structures, rock mass properties, and in situ stresses are necessary to assess the excavation method, rock support, and long-term stability of the rock mass (Brown, 2003). The large-scale structures and rock mass characterization become even more critical with increasing size and depth for underground mining and civil projects including block cave mining operations, transportation tunnels, deep nuclear waste repositories, enhanced geothermal energy systems, and regional water resources.

As these underground, large-scale projects continue to go to deeper depths and into a higher stress environment, the potential for slip along fracture and fault surfaces increases; as well as, increased need to characterize the intermediate and major structures within the rock mass. Major structures include large-scale, regional structures and fault systems with lengths greater than 1,000 meters (m) (3,280 feet (ft)). Preliminary desktop studies and ground-truth mapping aid in the early identification and characterization of the major structures, which allow incorporation of the large structures as into the project design and help to mitigate potential risk by modeling these features as discrete, individual structures. The real challenge, however, are identification and characterization of the intermediate structures in the underground environment, which are not easily observed with surface or outcrop mapping and are numerous enough that they cannot be treated as individual structures. The most critical intermediate structures include large fractures (intermediate discontinuities) and minor faults (major discontinuities) at the scale of 50 to 250 m (165 to 820 ft) in diameter with the potential of induced fracture and fault slip by seismic loading or stress redistribution with excavation.

During feasibility-level investigations, the identification of intermediate structures is especially difficult due to lack of information about the project site and therefore, data collection is often limited to borehole sampling. When restricted to borehole data, significant effort is expended on obtaining oriented core and/or televiewer logs to derive critical information regarding the presence of major faults, fracture network characteristics including spacing (intensity), orientation, size (persistence), and spatial attributes of the discontinuities within the rock mass and which are critical to accurately model the fracture network for a given site. However, the small observation window (Borehole wall diameter for BQ to PQ sizes: 6.0 to 12.3 centimeters (cm) or 2.4 to 4.8 inches in diameter) that the borehole affords is a severe limitation in the evaluation of the fracture size distribution (potentially spanning millimeters to kilometers) for the rock mass and therefore, a greater uncertainty in knowledge of the fracture network characteristics.

A stochastic solution to address the above limitations involves the use of Discrete Fracture Network (DFN) engineering methods, which can be effectively used to extrapolate data between large-scale, regional structures and discontinuities identified from small-scale borehole investigations in order to aid in quantifying the intensity and persistence of intermediate structures in the rock mass. The understanding and characterization of intermediate structures can be beneficial, if not critical, to successful underground excavation and construction projects.

#### **1.1** Thesis Objective and Scope

The research performed investigates DFN reliability, concluding with a comparative analysis of DFN model projections derived from borehole to shaft scale discontinuity data to evaluate the challenges of extrapolating discontinuity data across different scales. This research was conducted in collaboration with the Rio Tinto Centre for Underground Mine Construction (RTC-UMC), Centre for Excellence in Mining Innovation (CEMI), and Resolution Copper Company (RCC), and involved the additional input of Dr. Steve Rogers from Golder Associates, providing guidance on the use of their DFN modeling software, FracMan.

The central objective of the research was to investigate the validity and reliability of DFN models generated using data from limited sources, following a similar to work flow used on deep mining projects to forecast rock mass discontinuity geometric characteristics (orientation, spacing and persistence). The thesis is divided into two main sections: (1) an investigation of DFN reliability based on a comparative analysis of synthetic DFN models;

and (2) an analysis of discontinuity data provided by RCC across different scales (borehole with 0.063 m (0.2 ft) versus shaft with 10 m (30 ft) respective diameters).

The first of these investigations involves utilization of a synthetic data set in which a DFN is generated with known characteristics. A borehole investigation is then simulated to collect observed fracture data from the model, which is subsequently used to generate different DFN realizations. The generated DFN models are then compared to the original known DFN to measure similarity (or the representativeness). The results of the synthetic borehole investigation are then used to provide guidelines for optimizing feasibility-level drilling investigations with respect to gathering the required data for DFN modeling, showing where there are diminishing returns related to the volume of data collected, and the reliability of the DFN produced.

The second section of the thesis focuses on the analysis and DFN modeling of discontinuity data provided by RCC from their Resolution Mine project in Arizona, USA. This compares the discontinuity data derived from core logging and downhole televiewer data of a deep geotechnical borehole (RES-008 and RES-008A, telescoped borehole) with discontinuity data derived from photogrammetry data of a co-located deep shaft (Shaft 10). A DFN model was produced with the borehole data and sampled with a synthetic shaft using the same techniques developed in Part 1 of the thesis. The discontinuity traces sampled with the synthetic shaft were then compared to the mine shaft photogrammetry data to evaluate the reliability of discontinuity size distributions between those observed at depth and those represented in the DFN model.

#### 1.1.1 Software

The FracMan software (version 7.5 academic) provided by Golder Associates was used for the analyses presented in this thesis. FracMan is a DFN modeling package that is able to model three-dimensional fracture networks through stochastic methods.

#### **1.2** Thesis Organization

This thesis is structured into the following chapters:

- Chapter 2: Literature Review
  - A literature review is presented on the block cave mining method, followed by a summary review on feasibility-level geotechnical investigation techniques for obtaining the data required for preliminary DFN modelling.
- Chapter 3: Synthetic Borehole Investigation
  - A borehole investigation is simulated with DFN models. The results of which are used to provide guidelines for optimizing feasibility-level borehole investigations, showing diminishing returns related to data collection, and reliability of the resultant DFN.
- Chapter 4: Borehole to Shaft Comparison
  - The analysis and DFN modeling of discontinuity data provided by RCC. This compares borehole discontinuity data with shaft photogrammetry data. The produced DFN model was used to evaluate the reliability of discontinuity persistence distributions.
- Chapter 5: Conclusion and Future Work
  - Findings of this research are summarized and recommendations are provided for further research work.

### **Chapter 2: Literature Review**

The focus of this thesis is related to the characterization of a three-dimensional rock mass with limited site knowledge, specifically tailored toward borehole data, and how to improve the utilization and reliability of this knowledge for future underground construction. Limited site knowledge is often the case for greenfield sites and feasibility-level geological investigations; there are many different types of projects where this scenario applies. For this thesis, site investigations pertaining to block cave mining projects was the primary focus. The following sections in this chapter provide a brief background on block cave mining, investigation methods, data collection for feasibility-level geotechnical investigations, and DFN model input requirements for the collected data.

#### 2.1 Block Cave Mining

The block cave mining method has been in practice for over 100 years; it is a preferred method for underground mining of well fractured, weak, massive ore bodies, for example those associated with kimberlite pipes (diamonds) or porphyry deposits (copper). Block cave mining is a form of mass mining, which is a large-scale, high tonnage mining technique with daily production rates exceeding 10,000 tonnes per day (tpd) (Brown, 2003). The high production rates maximize the net present value (NPV) from large, lower grade ore bodies and/or especially deep, large ore bodies that would not be economical resources otherwise (Woo, Eberhardt, Elmo, & Stead, 2012). However, block cave mining does require a high initial capital investment for the infrastructure and development of the mine footprint, but has low operating costs once caving is initiated with utilization of gravity to fragment and crush the ore (Brown, 2003; RCC, 2013).

The precursor mining method to block caving was developed in the mid- to late-1800s with the underground iron and copper mines in the Upper Peninsula of Michigan; continuing into the early-1900s, the method was further developed in copper mines in Arizona, USA and asbestos mines in Quebec, Canada (Brown, 2003; Davide Elmo, 2014; Woo et al., 2012). The precursor mines utilized the top-slicing method, which was then replaced by shrinkage stoping with sub-level caving of the pillars, and by the 1920s, the block cave mining method

was fully established (Brown, 2003). For the block cave method, two mine levels are constructed before any mining takes place; these are the called the undercut level and the production level. The production level is just below the undercut level and covers the same footprint area. At the base of the ore body, the undercut level preconditions the rock mass by drill and blast to initially break up the ore. Drawbells are then drilled and blasted, connecting the undercut and production levels. The broken ore is drawn off through the drawbells creating a void, which starts the initial caving of the overlying ore. As the ore is continually drawn off, gravity will progressively fragment the rock and the cave will propagate upwards through the ore body or "block" and eventually to the overlying, un-mineralized host rock; which also caves causing surface subsidence. (Brown, 2003; Elmo, 2014; Laubscher, 2000; RCC, 2013; Vyazmensky, Elmo, & Stead, 2009; Woo et al., 2012).

The block cave mining method has changed and developed significantly with advances in the mining industry and technology, and the following two trends have been observed with these advances: 1) larger block heights, and 2) increasing depth of the undercut level. Historically, block cave mines used to be limited to block heights of 20 to 100 m (65 to 330 ft). These mines employed multiple block lifts at increasing depths to fully mine out large ore bodies. The initial undercut depth for these mines was 100 to 300 m (330 to 980 ft). After 1950, the mined blocks transitioned to heights exceeding 100 m (330 ft) and undercut depths of 600 m (1,970 ft) and greater. The footprint area of the undercut has also increased in size through time, further increasing the block size being mined (Woo et al., 2012). The first block cave operations mined relatively shallow, low-strength ore bodies that produce fine fragmentation at the drawpoints. Finely fragmented ore tends to chimney and potentially creates pillars of undrawn ore if the drawpoints are spaced too far apart, this limits drawbell size, spacing, and even the type of equipment used. Block caves have now moved into mining deeper, higher-strength ore bodies that produce coarser fragmentation, allowing wider spacing of drawpoints and larger equipment (Brown, 2003).

The trends of increasing block heights and depths are pushing block cave mines into environments of very high stresses and high confining pressures. The higher stresses change the rock mass behavior and push the production-level rock pillars closer to failure. Stable pillars are required to maintain safe access to the draw points and ore. While the higher confinement increases the rock mass strength through the interlocking of rock blocks; it also increases the brittleness of the rock mass (Kaiser, Amann, & Bewick, 2015). The high stress and confining pressure at great depths have the potential for pillar failure with increased energy release through spalling, rock bursts, shear slip, and reactivation of faults (Blenkinsop, 2008; Kaiser et al., 2015). Recognizing potential hazards by their failure mechanism is an essential part of assessing risks for the underground mine, where risk is defined by Kaiser, McKinnon, Duff, and Valley (2010) as follows:

#### *Risk* = *Likelihood* × *Consequence*

For any mining and engineering project, identifying and minimizing risk through mitigation is important. This is especially true for block cave mines at significant depth, sometimes greater than 1,000 to 1,500 m (3,280 to 4,920 ft), where the redistribution of stress through the mining process could lead to fracture and fault slip energy releases. The redistribution of stress could potentially cause severe to catastrophic consequences; including changes in cave propagation with altered fracture networks, drawpoint blockage with oversized fragments or large wedge failures, closure of mine opening, and equipment loss. (Kaiser et al., 2010; Laubscher, 2000)

Thus, understanding the geological structure and discontinuity network controls through site investigations and rock mass characterizations is paramount to the success of a block cave mining operation. Detailed geotechnical data on the intermediate- and major-scale structures, rock mass properties, and in situ stresses are necessary to assess the: 1) caveability of the orebody, and 2) excavation stability on the operating levels below, including the potential for fault slip and rockburst hazards when mining in a higher stress environment (Brown, 2003). The source of this essential data, especially at feasibility-level design, is almost always limited to borehole data. This is emphasized by Laubscher (2000), who notes that a number of caving operations are being designed solely on borehole information. The mine footprint and layout pattern are often determined early in the design process, and the

design is constrained with limited flexibility for change as the underground excavations begin (Kaiser et al., 2015; Laubscher, 2000).

#### 2.2 Block Cave Discontinuities of Concern

First, the term discontinuity should be defined. The definition of Brown (2003) is used in this thesis where a discontinuity involves any mechanical separation in a rock mass having zero to low tensile strength. This can refer to a joint, fracture, bedding plane, schistosity or foliation plane, fault, or fault zone. For this research, a discontinuity will generally refer to a joint and will be interchangeably used with the generalized term "fracture", to parallel the use of Discrete Fracture Networks. Discontinuities have been further sub-divided into the following size classes (Flores & Karzulovic, 2003):

- **Minor discontinuities:** Lengths up to 5 m (15 ft) and are numerous enough to be treated as a population, statistically speaking.
- Intermediate discontinuities: Lengths from 5 to 100 m (15 to 330 ft), but generally do not exceed 50 m (150 ft). These may affect several different underground excavations and are also sufficiently numerous to be treated as a population, statistically speaking.
- Major discontinuities: Lengths from hundreds of meters to a few kilometers and may affect several different underground excavations or the full footprint of the mine. The major discontinuities are usually regional features and are not as numerous as the minor and intermediate discontinuities; hence, these are treated deterministically.
  - Minor faults have been defined as those having a width less than 5 m (15 ft) thick and trace length between 100 to 1,000 m (330 to 3,280 ft) (Cosgrove, 2006).
  - Major faults have been defined as regional structures that are greater than 5 m (15 ft) thick and a trace length of 1,000 m (3.280 ft) or more (Cosgrove, 2006).

The discontinuities of interest for rockburst hazard analysis are large fractures (intermediate discontinuities) and minor faults (major discontinuities) between 50 and 250 m (150 to 820 ft) that have a high probability of fault slip (Martel & Pollard, 1989; Munier, 2006, 2010). The large fractures and minor faults will be described as intermediate structures. The intermediate structures are difficult to characterize during feasibility-level investigations, because: 1) the investigation windows are not at a scale to fully characterize these discontinuities (in terms of their persistence), and 2) the discontinuity itself, is not large enough to be observed regionally as a surface trace fault. This difficulty has been shown in the geological investigations at the Forsmark deep nuclear waste repository in Sweden where a gap in data for the fracture sizes was observed (Cosgrove, 2006). The data collected during the investigation process provided information on faults and fractures for trace lengths of 0.5 to 10 m (1.5 to 30 ft) and faults greater than 1,000 m (3,280 ft), but there was a data gap for fractures with a trace length between 10 and 1,000 m (30 to 3,280 ft) (Cosgrove, 2006).

Intermediate structures are the discontinuities of concern for footprint reliability of the production level pillars in a block cave mine due to the lack of data to fully characterize the rock mass and potential reactivation of the minor faults and/or future fault slip behaviors on larger fractures through the redistribution of stress (Kaiser et al., 2010; Munier, 2006, 2010). Fault slip along pre-existing faults and fractures have the potential for greater energy releases and a higher potential of severe damage to mine workings compared to the generation of new fractures and spalling to strainbursting rupture of intact rock. This is due to a portion of the energy in the stress redistribution that is consumed or expended in the generation of the new fractures surfaces through the intact rock, which greatly reduces the energy released (Sainoki & Mitri, 2014), relative to the energy stored along asperities for a critically stressed fault (similar to earthquakes). Laubscher (2000) discussed the energy release level with respect to the Richter Magnitudes (M) and showed that shear rupture via fracture propagation through intact rock ranges between M2.0 to M3.5, and fault-slip along an existing fault surface ranges between M2.5 to M5.0. Fault reactivation is commonly linked to extensional fracturing and new fault propagation by extensional fracture linkage through rock bridges (Blenkinsop, 2008; Naoi et al., 2015).

The orientation of the intermediate structures within the stress field also plays a part in the potential of a fault-slip event (Moeck, Kwiatek, & Zimmermann, 2009). For block cave mines, the intermediate structures oriented with an inclination of 45° or greater have the highest probability for a fault slip failure (Laubscher, 2000). However, discontinuities and minor structures that are flat dipping (angled 45° or less) should not be ignored as they are the most significant structures for shear and gravity failures (Laubscher, 2000).

#### 2.3 Rock Mass Characterization

#### 2.3.1 Classification Systems

Before a geological investigation takes place, it is important to understand the main rock mass classification systems, required parameters, and limitations associated with the characterization that may affect the project. The four main rock mass classifications are the following:

- 1. Rock Tunneling Quality index (Q) (Barton, Lien, & Lunde, 1974; Barton, 2002)
- 2. Rock Mass Rating (RMR) (Bieniawski, 1976, 1989)
- Modified Rock Mass Rating (MRMR) (Laubscher & Jakubec, 2001; Laubscher, 1977, 1990)
- Geological Strength Index (GSI) (Hoek, 2000; Hoek, Carter, & Diederichs, 2013; Hoek, 1994; Marinos, Marinos, & Hoek, 2005)

The RMR and Q systems were originally developed for use in tunnels and quick estimation guides for suggested rock support based on empirical data. The MRMR system modified the RMR system for use in the mining environment, with particular focus on block cave mines, and incorporated in situ stresses, stress changes and effects of blasting. The GSI system is a broader classification system and is used in conjunction with the Hoek-Brown criteria (Hoek & Brown, 1997) to calculate a strength envelope for the rock mass. The generally required parameters used in the listed rock mass classification systems include the following (inside the brackets indicate which of the previous listed classifications systems utilizes the parameter):

- Uniaxial Compressive strength (UCS) of intact rock material [2, 3]
- Rock Quality Designation (RQD) (Deere, 1964) [1, 2, 3]
- Number of discontinuity sets [1]
- Spacing of discontinuities [2, 3, 4]
- Size of discontinuity [2, 3, 4]
- Condition of discontinuities [1, 2, 3, 4]
- Groundwater conditions [1, 2, 3]
- Orientation of discontinuities [2, 3]
- Local stress conditions [1, 3]

Further detail on a specific rock mass classification can be found in the original source material, references provided. A few rock mass classification limitations are the following (Brown, 2003):

- RMR does not work well when characterizing poor quality rock masses.
- Q discontinuity set delineation is prone to sampling errors and is dependent on the robustness of the investigation.
- MRMR adjustments to RMR are subjective and dependent on expertise with no detailed guidelines provided.
- GSI rating may change dependent on the rock type that is not immediately observed in the charts.
- Intermediate and major structures are not given sufficient emphasis in the rock mass characterization at the mine scale. This is especially important for competent ore bodies, where the influence of larger structures is greater than incompetent ore bodies. (Laubscher, 2000)

## 2.3.2 Rock Mass Parameters

To fully utilize the rock mass classification systems, an understanding of their parameters is necessary in order to collect proper data. This collected data may also be carried forward into subsequent analyses of the spatial relationships between discontinuities with the use of DFN modelling.

The parameters of interest specifically to discontinuities during feasibility-level investigations are: 1) discontinuity orientation, 2) discontinuity sets, 3) RQD, 4) discontinuity spacing, 5) discontinuity size, and 6) discontinuity surface condition. Other important factors include the intact rock strength which is determined through laboratory testing and groundwater condition which is established through visual inspection and/or hydraulic investigations; these parameters are not within the scope of this thesis. A summary of the other parameters are described in more detail in the following sections.

### 2.3.2.1 Discontinuity Orientation

The orientation of a discontinuity is described with units of degrees and the notation forms of strike and dip (measured in quadrants or azimuth) or dip and dip direction (azimuth). The discontinuity orientation described using the dip and dip direction has become an industry standard, especially in the mining industry, and will be used for the remainder of this thesis. Priest (1993) lists orientation as one of the most important discontinuity characteristics relative both to other discontinuities and any engineering structure or excavation face.

#### 2.3.2.2 Discontinuity Set

Discontinuities are often observed to occur in sub-parallel groups or sets and are described with the group mean orientation and the degree of clustering around the mean; if the data set is robust. The degree of clustering for a discontinuity set is referred to as dispersion and measured with the Fisher k-value (Fisher, 1953). High k-values designate low dispersion or tight clustering of the set orientation values; as k-values decrease, the dispersion of the orientation values increase until the k-value equals zero where the orientation is uniformly random. Discontinuity sets can display spatial and directional relationships with local geological processes (i.e. rock deposition or cooling history, folds, faults, etc.) and regional tectonic activity (i.e. orogeny, rifts, etc.) (Hencher, 2012; Priest, 1993).

### 2.3.2.3 Rock Quality Designation (RQD)

The RQD (Deere, 1964) is an index of rock quality and is the summation of measured pieces of core greater than 10 cm (4 inches) divided by the total length of the core run. The pieces of core must be intact, sound rock with the length measured along the centerline of the core

or between the mid-points of the discontinuities, excluding mechanics breaks. The RQD recorded value is calculated as a percentage and is completed for each core run. The RQD calculation is recommended for rock core drilled with N-size or larger drill bit (approximately 50 mm core) ("Terminology and description of rock," 1998).

$$RQD = \frac{\sum Core \ pieces > 10 \ cm \ or \ 4 \ inches}{Total \ run \ length \ of \ core} \times 100$$

Priest (1993) notes that the RQD value is a form of discontinuity spacing and therefore, may vary significantly with the borehole orientation in a rock mass. It is noted that there is a level of double counting in the RMR classification with RQD being attributed as a type of discontinuity spacing and discontinuity spacing being a separate measured parameter in the RMR evaluation (Hencher, 2012).

#### 2.3.2.4 Discontinuity Spacing (Fracture Frequency)

Discontinuity spacing ( $\mu$ ), as defined by Priest (1993), is the measured length between one discontinuity and another and is linked to the reciprocal of discontinuity frequency ( $\lambda$ , also referred to as fracture frequency). The discontinuity spacing is measured on a linear line (i.e. borehole or scanline); it may vary significantly with the borehole orientation in the rock mass or the scanline along the rock exposure. Discontinuity spacing can be presented in the following three ways:

- **Total spacing:** The measured distance between a pair of immediately adjacent discontinuities along a line with specified location and orientation.
- Apparent set spacing: The measured distance between a pair of immediately adjacent discontinuities that are from the same discontinuity set along a line with specified location and orientation.
- Normal set spacing (also referred to as true set spacing): The measured distance between a pair of immediately adjacent discontinuities that are from the same discontinuity set along a line that is parallel to the mean normal of the set.

The apparent and true set spacing are related. The true set spacing can be obtained, when the apparent set spacing and line orientation is known, with the simple geometric equation (Priest, 1993):

$$\mu_n = \mu_a \cos \delta$$

Where:  $\mu_n = \text{mean normal set spacing (L)}$ 

 $\mu_a$  = mean apparent set spacing (L)

 $\delta$  = acute angle between the sample line and the normal of the set mean orientation (in degrees)

Similar relationships for fracture frequency are true since fracture frequency is the reciprocal of the spacing ( $\lambda = 1/\mu$ , L<sup>-1</sup>). The fracture frequency can be described with total, apparent, and normal (or true) terms. Fracture frequency can also be measured with a planar section through a rock mass (window mapping), and is denoted as the areal fracture frequency,  $\lambda_{a}$ .

The most fundamental frequency measurement is the volumetric fracture density,  $\lambda_v$  (Priest, 1993). While the volumetric fracture frequency is the ideal measurement, direct measurement is not possible with current technologies and must be estimated using the linear and areal fracture frequencies (Brown, 2003).

Fracture frequency or intensity values have also been classified in terms of the dimension of the measurement region and the dimension of the fracture (Dershowitz & Herda, 1992). This terminology has been updated and is currently used in the FracMan program (Golder, 2015); and will be referenced throughout this thesis. The designation is a "P" (from persistence), followed with two subscripts designating the measurement region (1: one dimensional line, 2: two dimensional surface plane, and 3: three dimensional volume) and the fracture attribute (0: number of fractures, 1: length of fracture traces, 2: plane or surface area of fractures, and 3: volume of fractures). The intensity terms and the descriptions are the following:

- P<sub>10</sub>: number of fractures per unit length of borehole ( $\lambda_l = L^{-1}$ )
- P<sub>11</sub>: length of fractures per unit length of borehole
- P<sub>20</sub>: number of fractures per unit area of window

- P<sub>21</sub>: length of fractures per unit area of window ( $\lambda_a = L/L^2$  or  $L^{-1}$ )
- P<sub>22</sub>: area of fractures per unit area of window
- P<sub>30</sub>: number of fractures per unit volume
- P<sub>32</sub>: area of fractures per unit volume ( $\lambda_v = L^2/L^3$  or  $L^{-1}$ )
- P<sub>33</sub>: volume of fractures per unit volume

The P<sub>10</sub>, P<sub>21</sub>, and P<sub>32</sub> intensity terms are the most used frequency descriptor terms.

#### 2.3.2.5 Discontinuity Size (Persistence)

Discontinuity size or persistence is described by Cruden (1977) as the percent of a plane area through the rock mass which is covered by discontinuities coincident with the plane. The discontinuity size could approximate the size of potential rock blocks that can form (coupled with spacing) and can have a positive or negative influence on the strength of the rock mass; making it one of the most important rock mass parameters (Wyllie & Mah, 2004). However, Priest (1993) notes that the discontinuity size is also one of the most difficult discontinuity characteristic to accurately measure or quantify. This is due to the fact that areal extent of discontinuities cannot be measured without disassembling the rock mass; therefore in practice, the persistence of the discontinuity is measured by the trace lengths exposed on rock faces using scanline surveys and window mapping (Brown, 2003; Hudson & Harrison, 1997; Priest, 1993). Cruden (1977) recommends that efforts should be made to measure the discontinuity length in a specific direction (i.e. direction of failure) or in the direction of dip and /or strike. The discontinuity size is related to intensity measurements and is correlated with the previously mentioned terms of areal fracture frequency ( $\lambda_a$  or P<sub>21</sub>) and volumetric fracture frequency ( $\lambda_v$  or P<sub>32</sub>).

#### 2.3.2.6 Discontinuity Condition

The condition of a discontinuity is based on qualitative descriptors and is difficult to measure and often is subjective to the geologist or engineer conducting the mapping. The characteristics included in condition descriptions include the amount and type of infill, degree of weathering and /or alteration, degree of aperture, surface geometry, surface roughness, and stress reduction factors (Priest, 1993).

#### 2.4 Geological Investigations to Collect Discontinuity Data

Feasibility-level geological investigations for Greenfield sites are often limited to borehole data and possibly scanline or window mapping of rock outcrops, but usually these occur later in the investigation process. Regional lineament mapping may occur as a desktop study and provide preliminary information on the general geology and structure. Before beginning a site investigation, it is important to understand the investigation method, potential errors, and associated biases inherent within the data collection method to limit or correct the errors and biases as much as possible. Potential errors and biases include the following (Brown, 2003; Einstein, Veneziano, Baecher, & O'Reilly, 1983; Kulatilake & Wu, 1984; Mauldon, Dunne, & Rohrbaugh Jr., 2001; Mauldon, 1998; S. D. Priest & Hudson, 1981; Priest, 1993; Song & Lee, 2001; Villaescusa & Brown, 1992; Zhang & Einstein, 1998):

#### • Measurement errors:

- Random measurement errors are reduced with larger sampling sizes.
  Recommended sample sizes include: 40 observation points per design set (Villaescusa & Brown, 1992), a general sampling of 100 points (Einstein & Baecher, 1983), to at least 200 discontinuity points (Priest, 1993).
- o Systematic sampling errors are not reduced with additional observation points.
- Orientation bias: The probability of a discontinuity being intersected by the sampling investigation depends on the relative orientation between the sample line or rock exposure and the discontinuity. If the plane of the discontinuity is perpendicular to the sampling line or window, the discontinuity has the highest probability (i.e., one) of intersection. The probability of encountering the discontinuity decreases as the angle between the sampling line or window and the discontinuity normal decreases and has the lowest probability (i.e., zero) if the discontinuity is parallel to the sampling line or window. The orientation bias may be corrected with a weighting factor first proposed by Terzaghi (Priest, 1993; Terzaghi, 1965).

$$w = \frac{1}{\cos \delta} \qquad \qquad \delta < 90^{\circ}$$

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where  $\delta$  = the acute angle between the discontinuity normal and the sampling line. Priest (1993) recommends a maximum weighting factor of 10 (minimum bias angle of 5.7°) to be used and the FracMan manual (Golder, 2015) suggests a maximum weighting factor of 7 (bias angle 8.2°).

- **Truncation bias:** Difficulty in measuring very small discontinuity trace lengths and therefore, discontinuities below a pre-determined cutoff length are not recorded. The truncation bias is considered negligible if the chosen cutoff length is small compared to the average length of the discontinuity population. Industry practices generally sets cutoff length between 0.1 to 0.5 m (4 inches to 1.5 ft) for scanline surveys and window mapping.
- **Censoring bias:** 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. Typical artificial boundaries imposed on mining operations include bench heights for open pit operations, and adit drive and shaft lift heights for underground operations. The censoring bias places an upper bound limit on the observable discontinuity trace length and can be reduced by increasing the sampling area to fully include the observed traces, which is not always possible.
  - Edge effects occur due to the finite area of the sampling window (Laslett, 1982).
- Length (size) bias: Larger discontinuities have a greater probability of being sampled than smaller discontinuities. This may be resolved or reduced by considering geometric characteristics of the contained or dissecting discontinuity traces. This bias occurs in two ways.
  - Larger discontinuities (larger surfaces) are more likely to appear on a rock exposure (outcrop or exposed rock face) than smaller discontinuities.
  - Longer discontinuity traces are more likely to appear in the sampling area than shorter discontinuity traces.

• **f-bias:** The intersection between a discontinuity and a rock exposure represents a trace length and chords produced by random intersections across the discontinuity surface and not necessarily the discontinuity diameter. This reflects that the trace length distribution may be different than the underlying discontinuity size distribution.

Subsequent characterization and quantification of the collected rock mass data will not only include the potential measuring errors and various biases, but also uncertainty and variability in the collected data. Uncertainty is described as the engineer's state of knowledge or lack of knowledge about a system, also referred to as "epistemic uncertainty"; and variability as the inherent randomness of the system or the natural heterogeneity of physical parameters, termed "aleatory variability" (Bedi & Harrison, 2013; Helton, 1997; Hora, 1996). Epistemic uncertainty, in theory, can be reduced or eliminated with the collection of additional data and is considered imprecise; whereas, aleatory variability is irreducible and considered precise. The level of uncertainty is dependent on the quantity and quality of the data collected. Therefore, epistemic uncertainty is a function of an insufficient quantity (small) and/or poor quality (imprecise) data set and aleatory variability is a function of a sufficient quantity (large) and high quality (precise) data set (Bedi & Harrison, 2013). However, it is important to note that a sharp or natural distinction between epistemic uncertainty and aleatory variability does not exist, but rather is a spectrum or dependent on the scale of measurement of the system and the required parameters (Hora, 1996).

Project knowledge begins in a state of epistemic uncertainty and moves toward aleatory variability through feasibility-level investigations, detailed design, and construction with data collection and continued updating of the site knowledge. This process of moving toward aleatory uncertainty with updates and revisions to the knowledge base utilizes the Bayesian approach (Bedi & Harrison, 2013; Bozorgzadeh, Dolowy-Busch, & Harrison, 2015). Bedi and Harrison (2013) note that increasing the sample population does not reduce variability, since variability is irreducible; however, increasing the degree of knowledge improves the understanding of variability.

Epistemic uncertainty and aleatory variability can also be related to the type of sampling used during the geological investigation, which include subjective and objective sampling methods. Subjective sampling collects select discontinuities and parameters evaluated as important by the field engineer or geologist. Subjective sampling is considered as limited knowledge and represents epistemic uncertainty, and thus, should be used in the appropriate type of model (Elmo et al., 2015). Objective sampling collects all discontinuities and their parameters intersecting the sampling line or area and allows a shift from epistemic uncertainty to aleatory variability of the sample data. The random process inherent in objective sampling is well suited for characterization with statistical analysis, and thus, in stochastic DFN modeling (Elmo et al., 2015).

For a geological investigation, assumptions should always be defined and registered before and during the investigation. As more data becomes available through further investigation and underground construction, the assumptions should be refined, validated, and adjusted as needed (Kaiser et al., 2015). The following sections will give further detail for borehole and rock exposure investigation using scanline surveys and window mapping.

### 2.4.1 Borehole Investigations

For Greenfield sites, and especially block cave mining projects, the rock mass and ore body cannot be observed directly and the characterization is often limited to borehole investigations (typical core sizes are NQ: 47.6 mm, HQ: 63.5 mm, PQ: 85 mm) (Kaiser et al., 2015). This lack of access, Brown (2003) notes, makes borehole data one of the most important and valuable data sets and often the only direct sampling or observation of the ore body. However, there are several challenges with borehole investigations described by Kaiser (et al., 2015) for traditional core logging which include:

- Differentiating between mechanical breaks and natural fractures resulting in a massive rock mass appearing blocky or of low quality.
- Differentiating between broken veins and open discontinuities resulting in a massive rock mass appearing blocky or of low quality.

- Discontinuity spacing or frequency due to difficulty in identifying discontinuity sets and is dependent on the robustness of the encountered features.
- Number of discontinuity sets is dependent on the robustness of encountered features and multiple boreholes drilled in various directions
- True discontinuity size or persistence cannot be observed.

Downhole televiewer (acoustical and /or optical) could aid in eliminating discontinuities that are non-representative (mechanical breaks and veins) and reduce the scatter of stereonet plots (Kaiser et al., 2015). The discontinuities observed in the core and accurate determination of the discontinuity orientations is critical for the assessment of cavability, fragmentation, and rock support requirements (Brown, 2003).

After discontinuity orientation is determined through oriented cores and /or downhole televiewer data, the orientation bias should be assessed using the Terzaghi weighting factor (Terzaghi, 1965) discussed previously. However, a borehole will still have a 'blind zone' or shadowed zone where parallel to sub-parallel discontinuities will be under sampled or missed entirely. Brown (2003) references that only the use of multiple boreholes at different orientations will resolve this sampling issue.

The weighting correction factor and additional boreholes do little to resolve the main limiting factor for borehole core data, with respect to the characterization of the rock mass and discontinuities, and that is the small observation window. The small diameter of the borehole severely limits any information for the discontinuity size (persistence), shape, or termination behavior (Brown, 2003; Kaiser et al., 2015).

## 2.4.2 Outcrop Mapping

Scanline surveys and window mapping of outcrops provide a larger dimensional scale than boreholes and allow more detailed data collection for discontinuity spacing, size, and spatial relationships with other discontinuities. Scanline surveys are linear lines placed on a rock exposure and discontinuities are measured for only the traces that intersect the line. Window mapping broadens the sampling area to a rectangular or circular area. As with borehole sampling, exposure mapping has some degree of sampling bias due to the sampling techniques being one dimensional (line) or two dimensional (plane) that sample a three dimensional rock mass and fracture network with three dimensional parameters (size, shape, and orientation) (Brown, 2003). Understanding the sampling technique chosen and the associated biases will limit and correct the sampling biases to provide quality data for use in data analysis and project design.

#### 2.4.2.1 Scanline Survey

Scanline mapping, also referred to as linear mapping, is similar to a borehole placed along a rock exposure with the added benefit of measuring discontinuity size. Scanlines are usually set up as horizontal lines at the base of a rock exposure (outcrop, mine bench, tunnel etc.) to limit edge effects of the sampling area (Cruden, 1977; Laslett, 1982); although, the scanline can be set up at any angle on the rock face. It is important to document the scanline orientation (trend and plunge) and the height above the scanline that may censor the discontinuity trace measurements. After the scanline is set up, only the discontinuities that intersect the line have their parameters recorded; with specific attention given to the trace length measurement and termination end descriptors. The potential terminations include: 1) intact rock, 2) against another discontinuity, or 3) extending beyond the observation area (Cruden, 1977; Priest & Hudson, 1981). The associated sampling biases for this method include: orientation, size, truncation, and censoring.

The orientation bias is corrected with the Terzaghi (1965) weighted correction factor and the use of multiple scanlines ideally located on exposures with varying orientations (Brown, 2003; Priest, 1993). The truncation bias is assumed negligible when the chosen cutoff length is small compared to the average observed trace length (Zhang & Einstein, 1998). To reduce size and censoring biases, Cruden (1977) suggests only sampling portions of the discontinuity trace above the scanline transect; this method is designated as semi-trace sampling. An additional bias potentially occurs for horizontal discontinuities being under sampled with scanlines due to: 1) horizontal discontinuities that rarely truncate typical rock exposures, and 2) horizontal discontinuities which are rarely the objective of scanline surveys (Cruden, 1977; Davy, 2006).
### 2.4.2.2 Window Mapping

Window mapping takes scanline surveys a step further from a linear or one-dimensional sampling technique to an areal or two-dimensional sampling technique. Window mapping investigations usually utilize a rectangular or circular shape, but may also be irregular. During the setup of the chosen rock exposure and window to be mapped, it is important to record the orientation of the rock face plane (trend and plunge) and the areal dimensions of the window (height and width or radius) that may censor the discontinuity trace measurements. After the window extent is set up, all discontinuities and their parameters contained within the window area are recorded; in contrast to scanline surveys, where only the intersecting discontinuity end-point descriptor which is used to estimate the mean length and intensity values for discontinuity sets. The end-point descriptors are coded as: 0 for no observable end-points or the discontinuity completely transects the window area; 1 for one observable end-point and the other end transecting the window area; and 2 where both end-points are observable within the window area.

Pahl (1981) proposed the window mapping technique with mine drive walls and utilized rectangular window areas. He was also the first to suggest grouping the discontinuity traces dependent on the observable end-points (0, 1, or 2) to estimate the mean trace length of the discontinuities. Pahl's (1981) method required the discontinuities to be parallel and assumed the discontinuity mid-points to be distributed randomly and homogeneously; while there are no assumptions for the discontinuity trace length distributions. Kulatilake and Wu (1984) expanded the rectangular window technique to use a pre-defined trace length distribution and the number of traces corresponding to the distribution.

Mauldon (1998) introduced new end-point estimators to calculate the discontinuity mean trace length and means density or areal frequency also using rectangular windows and parallel discontinuities. Zhang and Einstein (1998) and Mauldon et al. (2001) eliminated discontinuity orientation and trace length measurements, and assumptions of underlying trace length distributions with the use of circular windows. Lyman (2003) further demonstrated that the end-point estimators used to calculate the mean trace length by Pahl (1981), Mauldon

(1998), and Zhang and Einstein (1998) and areal frequency by Mauldon (1998), Mauldon et al. (2001), and Zhang and Einstein (1998) are unbiased estimators with minimum variance estimates and the most desirable estimators to use. However, Pahl (1981) did make note that mine geologists are often more interested in the longest potential trace length that occurs rather than the mean trace length.

The associated sampling biases for the window mapping method, similar to scanline surveys, include: orientation, size, truncation, and censoring. The orientation bias is corrected with the Terzaghi (1965) weighted correction factor and the use of multiple window areas with similar dimensions on adjacent rock faces of varying orientation, ideally orthogonally (Brown, 2003). The truncation bias is assumed negligible when the cutoff length is low (Zhang & Einstein, 1998). The size and censoring biases are greatly reduced with the larger area of the window mapping, and the newer end-point estimators corrected the censoring bias (Mauldon, 1998; Zhang & Einstein, 1998).

#### 2.4.2.3 Full Perimeter Intersection Criteria

The identification of intermediate structures is difficult since the true size of discontinuities can rarely be measured and there is no single parameter or property that can be used to uniquely identify a fracture as being large so multiple parameters are needed (Munier, 2010). Scanline surveys and window mapping better characterize intermediate structures compared to borehole data; which does not provide any indication for discontinuity size (persistence). Large-scale, subsurface excavations can provide an additional parameter for the identification of intermediate structures beyond the information for discontinuity persistence obtained with scanline and window mapping techniques. The discontinuity parameter is determined by whether or not the discontinuity intersection with the tunnel face or mine excavation wall can be traced along the entire section of the excavation and is termed the Full Perimeter Intersection, FPI (Munier, 2006, 2010). During a geotechnical investigation, the FPI does not quantify the full persistence of the discontinuity or fault length, but will provide some indication whether the observed discontinuity is significant and a lower bound for the mapped persistence. The FPI can be used to further evaluate the discontinuity size distribution.

This method has been suggested for the estimate of potentially conductive discontinuities for fluid flow (La Pointe, Wallmann, & Dershowitz, 1993) and potential fault slip behavior for intermediate structures in deep nuclear waste storage repositories (Munier, 2006, 2010). The identification of intermediate structures is critical for underground nuclear waste repositories, where large discontinuities could slip and damage the stored nuclear waste canisters. The potential fault movement of concern for the repository is a slip exceeding 5 cm (2 inches), as might be generated from a magnitude 6 earthquake (Munier, 2010).

### 2.4.3 Remote Sensing (Photogrammetry)

Remote sensing, specifically digital photogrammetry, has become a useful tool to complement conventional field mapping and discontinuity characterization of rock masses. Photogrammetry technology utilizes stereo images to produce a three-dimensional image and an associated point-cloud for the surfaces in the combined images. The rock exposure can then be analyzed remotely for discontinuity trace length measurements and other properties, making photogrammetry technology very appealing for mine operations where access time to rock exposure may be limited due to set mine schedules. Sturzenegger and Stead (2009) highlighted some of the advantages for photogrammetry which include the following:

- Ability to sample extended window areas that are not limited to the base of a rock exposure, therefore increasing the sampled data points and providing a more representative statistical data set.
- Ability to survey inaccessible rock exposures that are steep and /or high.
- Risk reduction of potential hazards for field personnel as the survey is completed in a remote, safe location (i.e. mine traffic, rock fall, etc.).
- Permanent record of the rock exposure for discontinuity characteristics and rock mass condition at a specific time.
- Discontinuity orientation measurements when conventional compass clinometer readings are affected by magnetic ore bodies.

The associated sampling biases for photogrammetry are similar to scanline and window mapping (orientation, size, truncation, and censoring) with additional biases of vertical

orientation and occlusion. These particular biases occur when a persistent discontinuity inclination is at the same angle as the camera line of sight, and the occlusion bias is specifically when portion of the rock face cannot be sampled due to protruding features obscured other features (Sturzenegger & Stead, 2009).

The methods to reduce and/or correct the associated biases in the data collected with photogrammetry are also similar to scanline surveys and window mapping. To minimize the occlusion bias, surveying the same rock exposure from multiple positions and angles is recommended, especially where there are significant changes in relief or perspective. Sturzenegger and Stead (2009) emphasis the occlusion phenomenon will occur with horizontal and vertical discontinuities and a direct consequence to the orientation bias. The orientation bias is corrected with the Terzaghi (1965) weighted correction factor, but special care is required for dealing with sub-parallel surfaces to the camera line of sight (Sturzenegger & Stead, 2009). The truncation bias is a function of the camera resolution. In order to accurately measure the discontinuity, the surface dimensions must be significantly greater than the image resolution. This gives a typical truncation bias between 0.2 to 0.6 m (0.7 to 2 ft) for digital photogrammetry (Sturzenegger & Stead, 2009). The size and censoring biases are reduced with the extension of the sample window area and inaccessible exposures becoming available for surveying; however, a censoring bias will continue to occur along the edges of sample window or discontinuity surface only partial measured in the sample region (Sturzenegger & Stead, 2009). Priest (1993) describes this with the f-bias where a portion of the discontinuity is hidden in rock mass or is eroded from the rock face.

#### 2.5 Discrete Fracture Network Model Requirements

Discrete Fracture Network (DFN) modelling can be used to create a synthetic rock mass from geological observations and data collected during the feasibility-level field investigations, and the models can be updated as additional information is collected throughout the life of the project. It is critical to understand the DFN model requirements, potential limitations and biases carried over from the sample collection method, and critical differences between the field discontinuity parameters and DFN input parameters (Elmo et al., 2015). The DFN

primary input requirements and secondary input properties derived from the collected discontinuity data are the following (Elmo et al., 2015; Golder, 2015):

- Primary discontinuity requirements:
  - Spatial location
  - o Orientation
  - o Intensity
  - Size (persistence)
  - Termination
- Secondary discontinuity properties:
  - o Aperture
  - o Shear strength
  - o Stiffness
  - o Transmissivity
  - o Storavity
  - o Termination percentage

The DFN primary and secondary parameters are input as probability distribution functions. The secondary discontinuity properties are not necessarily used in every DFN model and usually are determined through field descriptions of discontinuity condition and laboratory testing. A summary of the primary discontinuity parameters are described in more detail in the following sections.

# 2.5.1 Discontinuity Spatial Location

The FracMan program (Golder, 2015) determines the discontinuity spatial location during fracture generation with one of three algorithms, which include Enhanced Baecher, Nearest Neighbor, and Levy-Lee. The Baecher distribution uniformly locates the discontinuity centers in space using a Poisson process. The nearest neighbor distribution is based on fracture intensity decreasing exponentially with distance from a major, discrete feature, such as a fault. The Levy-Lee distribution is based on fractal patterns, usually derived from

discontinuity trace mapping. The Enhanced Baecher model is appropriate for many different applications and is well suited for small scale models (Elmo et al., 2015).

### 2.5.2 Discontinuity Orientation

The FracMan program (Golder, 2015) determines the discontinuity orientation during fracture generation with one of five probability distributions including Fisher, Bivariate Fisher, Elliptical Fisher, Bivariate Normal and Bivariate Bingham. The Fisher distribution is analogue to normal (Gaussian) distribution on a sphere and assumes symmetrical variation of orientation around the mean pole. This forces the variability in dip direction (or strike) to be equal to the variability in dip. The Bivariate Fisher distribution is defined by the probability density function with parameters specified by the user (Golder, 2015). The Elliptical Fisher distribution allows the dip and dip direction to have different amounts of variability. The Bivariate Normal distribution allows independent variations of dip and dip direction. The Bivariate Bingham distribution handles girdle distributions, such as fold structures. The orientation distribution used in DFN modeling should be determined with the field observations of the geologic structure.

The FracMan program also offers an option to "bootstrap" orientation data. The bootstrap method determines the discontinuity orientation in a generated fracture network through Monte Carlo values by multiple random sampling from selected orientation data (Golder, 2015). Elmo et al. (2015) recommends the bootstrap method for a discontinuity set with highly disperse scatter.

## 2.5.3 Discontinuity Intensity

Most field investigations and many rock mass classifications characterize discontinuity intensity as a linear fracture spacing; however, DFN models can reference the intensity value as a linear, areal, or volumetric measure, referred to as P<sub>10</sub>, P<sub>21</sub>, and P<sub>32</sub> respectively (Elmo et al., 2015; Rogers et al., 2015). The rock mass fracture network is ideally described with the P<sub>32</sub> value; however, P<sub>32</sub> cannot be directly measured (Brown, 2003; Dershowitz & Herda, 1992; Priest, 1993; Rogers et al., 2015), but P<sub>32</sub> can be calculated from P<sub>10</sub> or P<sub>21</sub> with simulation or analytical solutions (Rogers et al., 2015). The analytical solutions use a

conversion factor ( $C_{13}$ ) that is a function of the sample method orientation, fracture orientations, and discontinuity set dispersion around the mean pole (Rogers et al., 2015).

# 2.5.4 Discontinuity Size (persistence)

The discontinuity size (persistence) is an important parameter in DFN models, but is often not available or is limited during feasibility-level investigations (Elmo et al., 2015). The discontinuity size parameter, collected with scanline surveys and window mapping methods, need to account for trace length truncation and censoring biases. Also, the DFN required discontinuity size input value corresponds to the discontinuity radius, not necessarily the discontinuity trace length measured on rock exposures in the field or the apparent radius evaluated with processed images for remote sensing (Elmo et al., 2015).

## 2.5.5 Discontinuity Termination

The discontinuity termination is often overlooked during field investigations; and therefore, not collected. Discontinuity termination data can provide hierarchal structure for the associated discontinuity sets and relates to fracture connectivity; which is useful in evaluation of both stability and permeability of the rock mass (Elmo et al., 2015).

# **Chapter 3: Synthetic Borehole Investigation**

There are numerous geotechnical modeling programs available today with design capabilities that span simple kinematic wedge analyses to sophisticated discontinuum-based numerical modeling analyses. The type of modeling software chosen for a certain analysis typically depends on the quality and quantity of data available and the project needs. However, no matter the sophistication or complexity of the analysis method chosen, the reliability of the results (and any subsequent design) will be limited by the quality and reliability of the data used to conduct the analysis. Therefore, in the preliminary investigation stage of any geotechnical project, it is important to understand the best available methods in collecting the required data and how to modify the drilling program during the early investigation stages if necessary.

Budgeting and line item costs are important factors in geotechnical drilling programs. For feasibility level drilling investigations, budgets are often limited and very little may be known about the project site. This can make it difficult to properly budget the number and length of the investigative boreholes to required effectively minimize geological uncertainty, and there is often little flexibility in the investigation program once the project budget is finalized. Location of boreholes may be determined before the project begins with road and drill platform construction which is typically completed before the mobilization of the drill rig and crew. Borehole orientation has the most flexibility to be changed at any stage of the investigation. As can the borehole length, to some extent, recognizing that if deeper boreholes than budgeted are required this will limit or reduce the number and/or length of subsequent boreholes to maintain the program budget.

DFN modelling was undertaken here with two objectives: 1) to better understand the reliability of DFN models generated from borehole discontinuity data, and 2) to investigate how feasibility-level drilling investigations impact data reliability and how these investigations may be improved (recognizing that data is often limited at the beginning of the program). This involved a novel experiment in which a borehole investigation was simulated using a DFN model seeded with a known fracture network, referred to here as the "baseline". The baseline DFN was then sampled using a series of synthetic ("exploration") boreholes of

various lengths and orientations. The discontinuity data collected from these exploration borehole(s) was corrected with the Terzaghi correction factor and then used to generate a second ("model") DFN, following a similar work flow that would be used on a project requiring the development of a DFN based on borehole investigation data. The baseline and model DFN were then compared for similarity to estimate how well the sampled data was able to replicate the known original fracture network. Secondary ("comparison") boreholes were used to calibrate the effectiveness of the synthetic model network development. The comparison boreholes were located at the same exact location as the initial exploration boreholes to sample the model fracture network in the same manner as the original fracture network was sampled. The comparison boreholes were used in a similar way as would be done to validate a site model representative of the investigation borehole data. Figure 3.1 depicts the simplified steps used in the synthetic borehole investigations.



Figure 3.1 Method used in synthetic borehole investigation showing comparative analyses performed.

The generated networks were systematically sampled to assess the impact on borehole data collection with respect to the borehole spatial location, orientation, and the amount or intensity of fractures encountered. These three scenarios were evaluated separately to: i) reduce the variables evaluated at one time, ii) limit any interaction the variables might have

with each other, and iii) understand how the variables might impact an investigation and the quality of the data collected.

The baseline DFN used in the synthetic investigation represents a fracture network specific to a single geological unit (i.e., a single-domain). Also not represented is any heterogeneity that would be associated with interactions near the contact zones with adjacent geological units. The fracture network was modeled as a crystalline rock mass with homogenous fracturing throughout the region. Stochastic algorithms were used in the fracture network generation; twenty-five (25) realizations were run for each of the different scenarios using macro subroutines written with a loop function to evaluate the trend in the DFN model outputs.

### 3.1 Input Parameters and Baseline Model

The modeled baseline fracture network represents a single-domain crystalline rock mass with homogenous fracturing throughout. The model space was set as a standard box region with side lengths of 200 m (655 ft), giving a model volume of 8 million cubic-meters (Mm<sup>3</sup>) (280 million cubic feet). The fracture sets were generated with the same input (seed) parameters for each of the synthetic models for simplicity. The following definitions were applied to each set:

- Fractures were four-sided polygons, clipped at the outer region.
- An "Enhanced Baecher" model was used to generate the fracture locations.
- A target intensity P<sub>32</sub> value of 0.2 fractures per meter (m<sup>-1</sup>) (0.06 fractures per foot) was used, giving an approximate spacing of 5 m (15 ft).
- A Fisher distribution was applied to all discontinuity sets.
- An exponential size distribution with a mean radius of 30 m (100 ft) was used.

The generated baseline DFN was modeled both as an inclined fracture network and a vertical-horizontal fracture network. Both networks contained three discontinuity sets. The discontinuity set orientations used were as follows (provided in dip/dip direction):

- Inclined fracture network: 45°/025°, 45°/115°, and 45°/205°.
- Vertical-horizontal fracture network: 15°/295°, 80°/070°, and 80°/160°.

The stereonet plots showing the inclined and vertical-horizontal discontinuity sets are shown in Figure 3.2.



Figure 3.2 Stereonet plots of the inclined and vertical-horizontal fracture network inputs.

The fracture set dispersion value was defined with the same value to reduce variables in the model; however, the inclined and vertical-horizontal fracture networks were separately modeled with three different dispersion values for the discontinuity sets. The dispersion values used were 5, 20, and 80 (Figure 3.3); giving the orientation population a respective plus or minus of approximately 65°, 30°, and 15° from the mean pole of the discontinuity set calculated with the Fisher equation of the dispersion on a sphere (Fisher, 1953).



**Figure 3.3** Stereonet plots depicting the dispersion values of 5, 20, and 80, respectively from left to right, giving the orientation population a respective plus or minus of approximately 65°, 30°, and 15° from the mean pole of the discontinuity set using the Fisher equation of the dispersion on a sphere (Fisher, 1953)

#### 3.1.1 Borehole Spatial Comparison

For feasibility-level drilling investigations, the locations of the boreholes to gain the most information with the least amount of effort (cost) is an important consideration. Each mobilization of a drill rig to a new location will cost project time and money. The value added of the additional data is weighed against the additional effort to obtain the data and how beneficial it is to the project.

To assess the impact of the spatial distribution of boreholes on data collection (assuming a single-domain crystalline rock fracture network), five different synthetic investigations were simulated. The varying investigations maintained a total project drill length of 200 m (655 ft) (an overall constraint) that was equally divided between the boreholes. The five synthetic drilling investigations consisted of the following:

- One borehole at 200 m (655 ft)
- Two boreholes, each at 100 m (330 ft)
- Three boreholes, each at 66.7 m (220 ft)
- Four boreholes, each at 50 m (165 ft)
- Five boreholes, each at 40 m (130 ft)

The boreholes were all vertical (inclined 90° from horizontal) and systematically placed in the model region on a simple grid pattern. The simple systematic grid pattern was chosen with the model consideration of a greenfield site where discontinuity data has not been previously collected and therefore, the purpose of the boreholes is to collect baseline discontinuity data. The first borehole in the investigations was located in the center of the model region; each subsequent borehole was added to the center of the outlying quadrants to maximize the spatial sampling of the model region. To be consistent in the synthetic investigation layout, the additional boreholes started in the northeast quadrant and were added in a clockwise direction until there were a total of five boreholes. The northeast quadrant was chosen at random. The five spatial synthetic investigation layouts are shown in Figure 3.4.



4 Boreholes: 50 m (165 ft) length

5 Boreholes: 40 m (130 ft) length

**Figure 3.4** Borehole location (subset plan view) and length in the various five spatial synthetic investigation setups (north is into the page and up in the plan view in the smaller subset).

#### **3.1.2** Borehole Orientation Comparison

For feasibility-level drilling investigations, the number of boreholes and lengths are usually budgeted before the program begins. Changing the borehole location may be difficult or impossible due to many factors including: road and platform construction, regulatory requirements, access issues, or other considerations. However, in most cases borehole orientation may be easily modified.

To assess the impact of borehole orientation with respect to data collection in a modeled single-domain crystalline rock fracture network, twenty-seven (27) different synthetic investigations were conducted covering nine borehole setups with three different inclination angles for the oriented boreholes. The boreholes were systematically placed in the model region on a simple grid pattern. The systematic grid pattern was chosen with the model consideration of a greenfield site where discontinuity data has not been previously collected and therefore, the purpose of the boreholes is to collect baseline discontinuity data. The first borehole in the investigation was located in the center of the model region; each subsequent borehole was added to the center of each quadrant and then on the centerline between each of the quadrants to maximize the spatial sampling of the model region. The boreholes started in the northeast quadrant and were added in a clockwise direction until there was a total of nine boreholes. The northeast quadrant was chosen at random. The borehole spatial locations in the synthetic investigations are shown in Figure 3.5.



**Figure 3.5** Borehole spatial locations in the various nine angle comparisons for the synthetic investigation setups (north is up in the planar view in the smaller subset).

The first borehole in each investigation was inclined  $90^{\circ}$  (vertical) and the additional eight boreholes were inclined from horizontal at  $90^{\circ}$ ,  $70^{\circ}$ , or  $55^{\circ}$ . The additional boreholes in a given model were inclined at the same angle to limit the number of variables. The orientation direction of the inclined boreholes was systematically varied with each borehole, starting due south and rotating clockwise with each subsequent borehole. Each borehole in 36



the modeled investigations was 200 m (655 ft) in length. The borehole locations and orientations in the synthetic investigations are shown in Figure 3.6.

**Figure 3.6** Borehole orientation sampling of 3, 5, and 9 boreholes in the 90°, 70°, and 55° angle comparisons for the synthetic investigation setups (north is up in the planar view in the smaller subset).

## 3.1.3 Fracture Intensity Comparison

For any drilling investigation, from feasibility through to final design, the amount and quality of the data collected via the boreholes is critical. The addition or subtraction of drilled length to a borehole will cost or save time and money, as well as gain or lose data to the project.

The critical question then becomes whether adding extra length to a borehole will provide increased benefits with respect to data quality (reliability) or whether a borehole could be terminated early without a substantial loss of confidence in the data for quantity and quality.

To assess the impact on the amount of data collected with one borehole in a single-domain crystalline rock fracture network relative to the reliability of the data, the intensity or number of fractures in the fracture network was incrementally increased. A vertical borehole was located in the center of the region and the depth held constant at 200 m (655 ft). The fracture network started with an approximate spacing of 10 m (30 ft) between the fractures (P<sub>10</sub> intensity of 0.1 m<sup>-1</sup> or 0.03 ft<sup>-1</sup>). Fractures were incrementally added to the network and sampled until the fracture spacing was decreased to approximately 0.4 m (1.3 ft) (P<sub>10</sub> intensity of 2.5 m<sup>-1</sup> or 0.8 ft<sup>-1</sup>). Figure 3.7 depicts the borehole sampling at five different steps to illustrate the increased intensity of the fracture network.



Figure 3.7 Borehole sampling of fracture network at steps 1, 5, 10, and 25 from left to right.

The fracture network was simplified to first consider only a single discontinuity set to remove interaction between multiple discontinuity sets intersecting a borehole, and to allow relationships to be evaluated between the amount of data collected and the value added by including additional points. The discontinuity sets were modeled with dispersion values of 5, 20 and 80, as was done previously. The three discontinuity sets were taken from the single-domain crystalline rock fracture networks used in the synthetic models which had the

following orientations: 15°/295°, 45°/205°, and 80°/070°. The three discontinuity sets were chosen to demonstrate fractures that are perpendicular, inclined, and sub-parallel with respect to the borehole. After each discontinuity set was evaluated separately, the same procedure was performed with the three discontinuity sets in one network.

## 3.2 Synthetic Investigation Findings

Three synthetic investigation setups were modeled. These included: 1) borehole spatial comparison, 2) borehole orientation comparison, and 3) fracture intensity comparison. The generated fracture networks of these models were compared for similarity to the known baseline fracture network, which was then used to develop and provide guidelines for optimizing feasibility-level drilling investigations, and to progress from epistemic uncertainty (lack of knowledge) toward aleatory variability (characterization of the natural randomness of the discontinuity distributions). The analyses were carried out to show where there were diminishing returns for increasing efforts, relative to improvements in the reliability of DFN models produced. It is critical to understand how representative a DFN model is and its' limitations based on the source, quantity, and quality of the data obtained from the investigation program, in order to appropriately design the project at the current investigation level and state knowledge. The key findings for the synthetic investigation models are included in the following sections.

### **3.2.1** Borehole Spatial Comparison

All of the summary, and box and whisker plots from the synthetic borehole spatial investigation model output can be found in Appendix A . Figure 3.8 provides a sampling of three summary plots of the four parameters scaled for comparison of the discontinuity sets that are perpendicular, inclined, and sub-parallel to the reference borehole(s) from Appendix A . Based on analysis of those plots, the following conclusions are made:



**Figure 3.8** Summary plots of the four parameters scaled for comparison of the discontinuity sets that are perpendicular, inclined, and sub-parallel to the reference borehole, sampled from Appendix B

• The mean orientation for discontinuity sets derived from the generated fracture network match well with the baseline fracture network orientations from the DFN models; their reliability does not appear to be dependent on the length or spatial distribution of the boreholes as shown in Figure 3.8.

- The dispersion and intensity of a discontinuity set derived from borehole investigations are dependent on the length and/or the spatial distribution of the boreholes.
  - To maintain a project budget total drill length, the addition of more boreholes will not necessarily improve the accuracy of inferred spatial data for DFN purposes; especially where splitting a longer borehole into multiple boreholes substantially reduces the individual borehole lengths (e.g., one 200 m (655 ft) borehole vs. two 100 m (330 ft) boreholes). This is particularly true where sub-parallel discontinuities, with respect to the borehole, are present; shorter boreholes will not pick up the full distribution characteristics of the discontinuity set as shown in Figure 3.8.
  - However, if the boreholes are relatively similar in length and there is not a cost to the project budget total drill length, the addition of more boreholes may improve the accuracy of inferred spatial data (e.g., five 40 m (130 ft) boreholes vs. four 50 m (165 ft) boreholes). This is observed where inclined discontinuities, with respect to the borehole, are present; additional boreholes improved the distribution characteristics of the discontinuity set as shown in Figure 3.8.
  - Accordingly, drilling fewer boreholes with greater lengths may improve the reliability of the discontinuity set orientations determined, with added economic benefits. Again, this only applies to an investigation targeting a single geological domain. Where the investigation objectives include identifying multiple domains and determining geologic boundaries, more shorter-length boreholes may prove to be a better strategy than fewer longer-length boreholes.

### **3.2.2** Borehole Orientation Comparison

Supplementary summary, and box and whisker plots from the synthetic borehole orientation investigation model output can be found in Appendix B. Figure 3.9 provides a sampling of three summary plots of the four parameters scaled for comparison of an inclined

discontinuity set sampled with boreholes angled at 90°, 70°, and 55° from Appendix B (Shown on the next page). Based on analysis of those plots, the following conclusions are:

- The inclination angle and orientation direction of the boreholes has a significant impact on the reliability of the DFN derived from the collected data as shown in Figure 3.9 where the reliability of the parameter characteristics are increased or decreased dependent on the borehole orientation and the specific discontinuity set being sampled.
  - It is important to incrementally improve knowledge of the fracture network with each borehole. The subsequent borehole's orientation (inclination angle and direction) should be optimized relative to the target discontinuity sets using oriented boreholes, maximizing the quantity and reliability of the sample data.
  - Multiple oriented boreholes provide a more complete and reliable understanding of the fracture network.
- Inclined boreholes are not always better and depend on the orientation of the discontinuity sets present; boreholes that are sub-parallel to a discontinuity set may shadow or miss the discontinuity set completely within the blind zone of the borehole as shown in Figure 3.9 where the discontinuity set was missed due to being in the blind zone of borehole number 3 angled at 55° and this was not observed with the borehole number 3 angled at 90°.
  - To reduce or avoid the borehole's blind zones, it is recommended that during an investigation drilling campaign, the first borehole should be quickly analyzed before proceeding to determine the best angle and orientation of subsequent boreholes.



**Figure 3.9** Summary plots of the four parameters scaled for comparison of the discontinuity set where the data was collected with a borehole(s) angled at 90°, 70°, and 55°, sampled from Appendix B

## 3.2.3 Fracture Intensity Comparison

Supplementary summary, and box and whisker plots from the synthetic borehole intensity investigation model output can be found in Appendix C . Figure 3.10 provides sample from Appendix C  $\,$  of summary, and box and whisker plots for the dispersion parameter of

discontinuity sets that are perpendicular, inclined, and sub-parallel to the reference vertical borehole.



**Figure 3.10** Scaled summary plots, and box and whisker plots for the dispersion parameter of discontinuity sets that are perpendicular, inclined, and sub-parallel to the reference borehole, sampled from Appendix C

Based on analysis of those plots, the following conclusions are:

- Approximately 50 to 100 data points (with the Terzaghi correction applied) are required to adequately characterize the discontinuity set orientation distribution with respect to the dispersion parameter as shown in Figure 3.10.
- Discontinuity sets perpendicular to drilling are sensitive to the number of fractures sampled with respect to determining the dispersion value. The reliability of the model dispersion relative to the baseline dispersion is shown in Figure 3.10 and Table 3.1.

| Perpendicular<br>Discontinuity Set   |    | Number of fractures<br>encountered |     |     |  |
|--------------------------------------|----|------------------------------------|-----|-----|--|
|                                      |    | 50                                 | 75  | 100 |  |
| Baseline Network<br>Dispersion Value | 5  | 20%                                | 15% | 10% |  |
|                                      | 20 | 8%                                 | 5%  | 5%  |  |
|                                      | 80 | 5%                                 | 5%  | 5%  |  |

**Table 3.1** Reliability of the Model DFN with a Perpendicular Discontinuity

 Set with the Number of Encountered Fractures

• Discontinuity sets inclined to drilling were somewhat less sensitive to the number of fractures sampled with respect to determining dispersion and is shown in Figure 3.10 and Table 3.2.

**Table 3.2** Reliability of the Model DFN with an Inclined Discontinuity Set with the Number of Encountered Fractures

| Inclined Discontinuity Set |    | Number of fractures<br>encountered |     |     |
|----------------------------|----|------------------------------------|-----|-----|
|                            |    | 50                                 | 75  | 100 |
| Baseline Network           | 5  | 15%                                | 12% | 10% |
| Dispersion Value           | 20 | 7%                                 | 5%  | 5%  |
|                            | 80 | 3%                                 | 3%  | 3%  |

• A sub-parallel discontinuity set relative to the drilling direction was less sensitive to lower dispersion values but more sensitive to higher dispersion values and is shown in Figure 3.10 and Table 3.3

| Sub-parallel<br>Discontinuity Set |    | Number of fractures<br>encountered |    |     |
|-----------------------------------|----|------------------------------------|----|-----|
|                                   |    | 50                                 | 75 | 100 |
| <b>Baseline Network</b>           | 5  | 12%                                | 5% | 2%  |
| Dispersion Value                  | 20 | 5%                                 | 5% | 2%  |
|                                   | 80 | 5%                                 | 2% | 2%  |

**Table 3.3** Reliability of the Model DFN with a Sub-parallel Discontinuity

 Set with the Number of Encountered Fractures

• Similar results were observed when the three discontinuity sets were modeled as one network and not individually.

### 3.3 P<sub>10</sub> Scaling Factor

From the synthetic borehole investigations, it was observed that the generated fracture network was less dense than the baseline fracture network when the discontinuity sets were sub-parallel to the borehole(s) as shown in Figure 3.11, even with use of the Terzaghi correction factor in the bootstrap process. The Terzaghi correction becomes unreasonable large for sub-parallel discontinuities to the sample borehole, and the maximum Terzaghi correction specified in FracMan limits the DFN generation. The inclined discontinuity set generated a much more accurate DFN than the sub-parallel discontinuity set. Decreased intensity (or fracture density) was observed for the fracture network generated with a subparallel discontinuity set to the borehole (10-40% reduction of the intensity to the baseline network shown in the bottom graphs of Figure 3.11), compared to a fracture network generated with an inclined discontinuity set to the borehole (0-15% reduction of the intensity to the baseline network shown in the top graphs of Figure 3.11). A consideration here is that the DFN modeling was performed using a bootstrapping method available in FracMan. The bootstrap method involves utilizing available borehole data to generate fractures deterministically rather than as a random distribution. This is generally favored when there is good spatial coverage by the data and during feasibility-level investigations when sample data is limited to boreholes. Therefore, accurate modelling of the fracture network intensity

(or density) is important early in the project when major decisions are made for block cave mines and are difficult or impossible to change later in the design process.



**Figure 3.11** Decreased intensity (or density) of fracture network generated with a sub-parallel discontinuity set to the borehole (bottom graphs); compared a fracture network generated with an inclined discontinuity set to the borehole (top graphs). The inclined discontinuity set generated a more accurate DFN than the sub-parallel discontinuity set, even with the use of the Terzaghi correction factor.

To better understand how the discontinuity sets were affected when using the bootstrap process used within FracMan, the synthetic borehole investigation models were modified to evaluate a scaling factor for the bootstrap method. The baseline DFN was seeded with a known fracture network and sampled using a series of synthetic exploration, as was done in

the synthetic borehole investigations. The discontinuity data collected from these exploration borehole(s) was corrected with the Terzaghi correction factor and then used to generate multiple model DFNs using different  $P_{10}$  scaling values for the bootstrap process. The baseline and model DFN were then compared for similarity to estimate how well the sampled data was able to replicate the known original fracture network. Figure 3.12 depicts the simplified steps used in the P10 scaling factor investigations.



Figure 3.12 Method used in P<sub>10</sub> scaling factor investigation showing comparative analyses performed.

The baseline DFN represents a fracture network specific to a single geological unit (i.e., a single-domain) and any heterogeneity that would be associated with interactions near the contact zones with adjacent geological units is not represented. The fracture network was modeled as a crystalline rock mass with homogenous fracturing throughout the region. Stochastic algorithms were used in the fracture network generation; fifteen (15) realizations

were run for each of the different scenarios using macro subroutines written with a loop function to evaluate the trend in the DFN model outputs.

# 3.3.1 Input Parameters and P<sub>10</sub> Evaluation Setup

The modeled baseline fracture network represents a single-domain crystalline rock mass with homogenous fracturing throughout. The model space was set as a standard box region with side lengths of 200 m (655 ft), giving a model volume of 8 million cubic-meters (Mm<sup>3</sup>) (280 million cubic feet). The fracture sets were generated with the same input (seed) parameters for each of the synthetic models for simplicity. The following definitions were applied to each set:

- Fractures were four-sided polygons, clipped at the outer region.
- An "Enhanced Baecher" model was used to generate the fracture locations.
- A target intensity P<sub>32</sub> value of 0.2 fractures per meter (m<sup>-1</sup>) (0.06 fractures per foot) was used, giving an approximate spacing of 5 m (15 ft).
- A Fisher distribution was applied to all discontinuity sets.
- An exponential size distribution with a mean radius of 30 m (100 ft) was used.

The generated baseline DFN was modeled both as orthogonal or conjugate systems with three discontinuity sets, with two of the discontinuity sets being sub-parallel to the borehole(s). The fracture sets were varied so that the two sub-parallel sets were inclined relative to the borehole(s) at the following inclinations: 10°, 15°, 19°, 28°, and 45°. The discontinuity set orientations used were as follows (provided in dip/dip direction):

- Orthogonal Fracture System:
  - Inclined fracture network: 45°/025°, 45°/115°, and 45°/205°.
  - o Inclined fracture network: 62.5°/070°, 62.5°/160°, and 32.5°/295°.
  - o Sub-parallel network:  $71^{\circ}/070^{\circ}$ ,  $71^{\circ}/160^{\circ}$ , and  $19^{\circ}/295^{\circ}$ .
  - Sub-parallel fracture network: 75.5°/070°, 75.5°/160°, and 17°/295°.
  - o Sub-parallel fracture network: 80°/070°, 80°/160°, and 15°/295°.
- Conjugate Fracture System:

- o Inclined fracture network: 45°/025°, 45°/145°, and 45°/205°.
- o Inclined fracture network: 62.5°/085°, 62.5°/145°, and 32.5°/295°.
- Sub-parallel fracture network: 71°/085°, 71°/145°, and 19°/295°.
- Sub-parallel fracture network: 75.5°/085°, 75.5°/145°, and 17°/295°.
- Sub-parallel fracture network: 80°/085°, 80°/145°, and 15°/295°.

The stereonet plots showing the orthogonal or conjugate systems are shown in Figure 3.13.



Figure 3.13 Stereonet plots of the orthogonal and conjugate fracture network.

The fracture set dispersion value was defined with the same value to reduce variables in the model; however, the modelled fracture networks were separately modeled with three different dispersion values for the discontinuity sets (5, 20, and 80; as was done with the synthetic investigation models); giving the orientation population a respective plus or minus of approximately  $65^{\circ}$ ,  $30^{\circ}$ , and  $15^{\circ}$  from the mean pole of the discontinuity set calculated with the Fisher equation of the dispersion on a sphere (Fisher, 1953).

To assess a P<sub>10</sub> scaling factor when using the bootstrap method in FracMan to generate a fracture network from the sampled exploration borehole data, the P<sub>10</sub> scaling factor was varied from 0.8 to 2.0 (increments of 0.05) and the generated networks compared to the baseline network to evaluate the most appropriate value for the scaling factor. The fracture network was sampled with one through five boreholes to evaluate if there were any difference between using the bootstrap method with one versus multiple boreholes. The boreholes were all modeled as vertical, 200 m (655 ft) in length, and systematically placed in the model region on a simple grid pattern as was done with the synthetic investigation models. The first borehole in the investigations was located in the center of the model region; each subsequent borehole was added to the center of each quadrant. The additional boreholes started in the northeast quadrant and were added in a clockwise direction until there were a total of five boreholes in the model region.

### 3.3.2 P<sub>10</sub> Evaluation Findings

From the  $P_{10}$  comparative analyses, it was observed that the reliability of the bootstrapped DFN model generation was not impacted by the fracture system (whether it was an orthogonal or a conjugate system), the network dispersion value, or the number of exploration boreholes. However, it was found that the fracture set inclination relative to the borehole (angle between the discontinuity set and the borehole) did impact the subsequent DFN generation. For the bootstrap method, scaling factors were derived for correcting the  $P_{10}$  parameters used in DFN modelling, an example calculation from one plot from Appendix D of the intensity parameter for the discontinuity sets of a fracture network is shown in Figure 3.14 (all of the box and whisker plots from the model output can be found in Table

3.4 and is dependent on the number of fractures that are sub-parallel to the borehole ( $20^{\circ}$  or less), and the average angle, in degrees, between the fracture and borehole.



Figure 3.14 Example calculation for the P<sub>10</sub> Scaling Factor.

To evaluate the appropriate scaling factor to use with the bootstrap method, the following steps are: 1) evaluate the average angle between each discontinuity set and the reference borehole, and 2) use the two smallest angles to lookup the appropriate scaling factor from Table 3.4 to use.

|   |      | Fracture Set 1                              |      |      |      |
|---|------|---|------|------|------|
|   |      | (degrees inclined with respect to borehole) |      |      |      |
|   |      | >20°  | 20°  | 15°  | 10°  |
| <b>Fracture Set 2</b><br>(degrees inclined with<br>respect to borehole) | >20° | 1.00  | 1.02 | 1.05 | 1.07 |
|   | 20°  | 1.02  | 1.05 | 1.07 | 1.10 |
|   | 15°  | 1.05  | 1.07 | 1.10 | 1.12 |
|   | <10° | 1.07  | 1.10 | 1.12 | 1.15 |

Table 3.4 P10 Scaling Factor

\* Fracture network consisting of three discontinuity sets (third set is inclined greater than 20° with respect to the borehole)

\* To be used with the Terzaghi correction factor applied

When the  $P_{10}$  scaling factor is used with the bootstrap method, the scaling factor is applied to all of the fracture sets in the generated network and not just the sub-parallel sets. Therefore, it is critical to understand which fracture sets are important to the model and whether the increase in the number of fractures for one set will drastically affect the model. This scaling factor is recommended when there is limited data and two of the fractures sets are subparallel to the borehole(s). If multiple boreholes are being drilled, the scaling factors only apply if the boreholes all have the same orientation or similar angles with respect to the discontinuity sets. Applying correction factors that accurately model the network intensity will aid in providing representative estimates for in situ block sizes and the expected fragment size distribution.

# **Chapter 4: Borehole to Shaft Comparison**

Discontinuity data was provided by RCC, which was obtained from a deep geotechnical investigation borehole (RES-008/-008A) and co-located 10 m (30 ft) diameter deep shaft (Shaft 10). The borehole data was collected using conventional core logging and processed downhole televiewer data, which provided the orientation and depth of the fractures encountered with the RES-008/-008A borehole. The Shaft 10 data was collected from processed photogrammetry data, which provided orientation, trace length, and the x, y, and z coordinates of the discontinuities encountered in Shaft 10. The close proximity of the borehole and shaft (approx. 20 m (65 ft) at surface) presents an opportunity to ground truth the borehole discontinuity data projections within the DFN model with the documented shaft discontinuity data.

To facilitate this comparison, a DFN model was generated from the borehole data and then sampled using a synthetic model shaft. The discontinuity data sampled with the model shaft was subsequently compared to the discontinuity data documented in Shaft 10 to evaluate whether the intensity and fracture size distribution produced in the DFN model matched what was observed at depth in the shaft.

### 4.1 Local Geology and Ore Deposit

The local geology at the RCC mine site and the borehole data were reviewed and analyzed before building the DFN model. The geological unit lithology and structure for the RCC site is provided in the following sections.

### 4.1.1 Lithology

A desktop study of the geological units in the area (Ballentyne et al., 2003; Hehnke et al., 2012; Manske & Paul, 2002; RCC, 2013) and identified in the borehole are briefly described in the Table 4.1 (shown in order of youngest to oldest):

| Time Period               | Unit Name       |                               |  | Description  | Identified  |
|---------------------------|-----------------|-------------------------------|--|--|-------------|
|                           | -               |                               | 0  |  | in Borenole |
|                           | T <sub>al</sub> | Apache Leap formation         |  | Welded dacite tuff   | Yes         |
| Tertiary                  | T <sub>w</sub>  | Whitetail formation           |  | Massive conglomerate, medium bedded to massive sandstone, and thinly bedded siltstone  | Yes         |
| Cretaceous-<br>Tertiary   | KT <sub>i</sub> | Intrusive                     |  | Fine-grained felsic and quartz-eye porphyry dikes, sills, and stocks with phyllic alteration   | Yes         |
| Cretaceous                | K <sub>vs</sub> | Volcaniclastics               |  | Thick sequence volcaniclastic and siliciclatic (thick bedded<br>conglomerate and sandstone, and thinly bedded siltstone) with<br>propylitic alteration and hypogene mineralization | Yes         |
|                           | K <sub>qs</sub> | Quartzose                     |  | Medium bedded quartzose to feldspathic sandstone and siltstone<br>with propylitic and phyllic alteration   | Yes         |
| Pennsylvanian-<br>Permian | PP <sub>n</sub> | Naco group                    |  | Limestones and shales  | No          |
| Mississippian             | Me              | Escabrosa formation           |  | Limestones   | No          |
| Devonian                  | D <sub>m</sub>  | Martin formation              |  | Massive pyroxene skarn (altered interbedded limestone-dolomite<br>and siltstone) with chalcopyrite and pyrite veins and phyllic<br>alteration                                      | Yes         |
| Cambrian                  | €ь              | Bolsa formation               |  | Thinly bedded quartzite and siltite (meta-siltstone) with silicic alteration   | Yes         |
|                           | $p \in_{diab}$  | Diabase                       |  | Massive, medium grained diabase with phyllic alteration  | Yes         |
|                           | pEt             | Troy formation                |  | Quartzite  | No          |
|                           |                 |                               | Un-named   | Basalt flows   | Yes         |
| Pre-Cambrian              |                 | Mescal formation $(pC_{mls})$ | Limestone breccia grading to a marble              | Yes  |             |
|                           | p€y             | group                         | Dripping Spring formation ( $p \varepsilon_{ds}$ ) | Thinly bedded quartzite with phyllic alteration  | Yes         |
|                           |                 |                               | Dripping Spring formation ( $pE_{ds}$ )            | Shale  | No          |
|                           | p€ <sub>p</sub> | Pinal schist                  |  | Metamorphosed greenschist facies rocks   | No          |

**Table 4.1** Geological Units in the area of Resolution Mine and identified in RES-008/-008A Borehole

The Pinal schist  $(p \in_{pi})$  is the regional basement unit for eastern Arizona with the Apache group nonconformably lying above, and the Troy quartzite  $(p \in_t)$  unconformably overlying the Apache group. The Pre-Cambrian Diabase  $(p \in_{diab})$  intrudes the Apache group  $(p \in_y)$  rocks where an upper sill intruded between the Dripping Spring formation  $(p \in_{ds})$  and Mescal formations  $(p \in_{mls})$  and a lower sill intrude below the Dripping Spring formation  $(p \in_{ds})$ . The diabase sills are regionally extensive and dilate the Pre-Cambrian section upwards of 100 percent.

The Pre-Cambrian rocks are unconformably overlain by the Paleozoic rocks, which are almost completely removed by erosion, with only portions of the Cambrian Bolsa quartzite  $(\mathcal{C}_b)$  and Devonian Martin limestone  $(D_m)$  encountered in the RES-008/-008A borehole. This erosion forms a disconformity between the Paleozoic and Mesozoic rocks above.

The Mesozoic rocks include the Cretaceous age quartzose ( $K_{qs}$ ) and volcaniclastic ( $K_{vs}$ ) rocks. The Cretaceous-Tertiary intrusives ( $KT_i$ ) is composed of a swarm of dikes 1,000 m (3,280 ft) wide and strike east-northeast that intrude through the center of the  $K_{vs}$  and  $K_{qs}$  units and is attributed to the Laramide orogeny. The Cretaceous aged rocks and intrusions are the dominate host rocks for the Resolution ore body.

The Cretaceous aged rocks are truncated by an angular unconformity and overlain by unmineralized Tertiary rocks including the Whitetail conglomerate ( $T_w$ ) and the Apache Leap tuff ( $T_{al}$ ). The un-mineralized overburden is upwards of 1,300 m (4,265 ft) thick for the  $T_w$ unit and up to 600 m (1,970 ft) thick for the  $T_{al}$  unit, with a northeast-thickening section. The geologic unit contacts as observed in the borehole are shown on the cumulative fracture intensity (CFI) plot generated from the RES-008/-008A borehole discontinuity data (Figure 4.1).



Figure 4.1 Cumulative Fracture Plot from the investigation borehole with the geological units.

#### 4.1.2 Structure

The area surrounding the RCC mine is located in the Basin and Range Provence, an extensional regime dominated by steeply inclined, normal faulting. The Resolution deposit is bounded by these steeply dipping faults and is situated in a down-thrown block or graben. The K<sub>vs</sub> unit is bounded by three main faults including the North Boundary Fault, the South Boundary Fault, and the West Boundary Fault; less dominate faults to the east include the Rancho Rio Fault, Devil's Canyon Fault, and the Conley Springs Fault. The West Boundary Fault is a steep, normal fault down-dropped to the east. This fault is masked on the surface by Tertiary aged rocks, but was encountered in historic underground mine workings just to the north (called "NS-5 West Fault" (Manske & Paul, 2002)). The North Boundary Fault is a steep normal fault and may be a jog or stepover fault and kinematically linked to the
West Boundary Fault (Hehnke et al., 2012; Manske & Paul, 2002). The South Boundary Fault is a complex fault zone, approximately 100 to 150 m (330 to 490 ft) wide, formed by two major sub-parallel, left-lateral, strike-slip faults and dips 60° to 80° NW (Manske & Paul, 2002). The known faulting within the Resolution graben are mostly normal faults that strike north to north-northeast, dip steeply to the west, and show down displacement to the west (Hehnke et al., 2012).

When the graben dropped during the Laramide-age extensional deformation, the  $K_{vs}$  unit was tilted 25° to the east-northeast (35° observed in historic underground mine workings (Ballentyne et al., 2003; Manske & Paul, 2002)). The tilting of the Resolution graben block is an assumed consequence of Tertiary-age displacement on the Devil's Canyon and Conley Springs normal faults (Hehnke et al., 2012). Un-mineralized overburden was deposited during the tilting of the K<sub>vs</sub> unit forming the angular unconformity with the Tertiary rocks. The overburden deposition during the tilting of the graben block is known because there is an angular unconformity of 12° between the T<sub>w</sub> and T<sub>al</sub> units, which is less than the angular unconformity between the K<sub>vs</sub> and T<sub>w</sub> units. (Ballentyne et al., 2003; Hehnke et al., 2012; Manske & Paul, 2002; RCC, 2013).

### 4.1.3 Ore Deposit

The Resolution deposit is a large, high grade copper-molybdenum (Cu-Mo) porphyry system. The hypogene mineralization of the ore body is not restricted to one lithology or geologic unit, and includes the Precambrian and Paleozoic age quartzites, carbonates, and diabase sills, and the Cretaceous age sandstones, volcaniclastics, and igneous intrusions. The deposit is a relatively structurally intact, dome-shaped mass. The upper boundary of the dome is defined by sporadic mineralization averaging less than 0.5 percent Cu to an abrupt transition to continuous 1.0 percent or greater assayed Cu (with the center averaging 2.0 percent Cu); this boundary is identified as the 1% Cu shell (Hehnke et al., 2012). Four stages of strong alteration and mineralization have been evaluated through dating, cross-cutting, and over-printing events and are described below (Ballentyne et al., 2003; Hehnke et al., 2012; Manske & Paul, 2002; RCC, 2013):

- 1. <u>Potassic alteration</u>: associated with dominant chalcopyrite rich mineralization and the early stages of mineralization.
- 2. <u>Propylitic alteration</u>: associated with epidote-bearing zones and is on the outward edges of the earlier potassic alteration zone.
- 3. <u>Quartz-sericite alteration</u>: associated with chalcopyrite, bornite, chalcocite, and pyrite mineralization and largely overprints the upper portion of the potassic alteration zone.
- 4. <u>Advanced argillic alteration</u>: consisting of kaolinite, dickite, topaz, alunite, pyrophyllite, and zunyite; also, associated with pyrite, bornite, chalcocite, and digenite mineralization and overprints the quartz-sericite alteration zone.

The higher Cu grade of the Resolution porphyry deposit, as compared to other porphyry deposits in Arizona, is dependent on lithology and alteration. The favorable host rocks at the Resolution deposit include carbonate, diabase, breccias, and volcaniclastic rocks; the less favorable host rocks are the quartzite, sandstone, and the Laramide-aged intrusive rocks. The favorable alteration is attributed to the superposition of the late stage argillic alteration over the earlier quartz-sericite alteration event (Ballentyne et al., 2003; Hehnke et al., 2012).

The  $K_{vs}$  unit with the igneous intrusions (KTi) through its center, host a significant percentage of the disseminated mineralization, totaling 27 percent of the deposit's Cu mineralization (12 and 15 percent, respectively). The Precambrian upper and lower diabase sills are also significant with 36 percent Cu mineralization, then the quartzite rocks with 17 percent, followed by the breccia and skarn rock types with 10 percent each (Hehnke et al., 2012). The copper resource has been evaluated by RCC to be approximately 1.7 billion tonnes at an average of 1.47 percent Cu and 0.04 percent Mo (RCC, 2013). The ultimate size of the ore body has not been fully established; however, the footprint defined by the 1% Cu shell is approximately 1,500 m (4,920 ft) in the north-northwest direction, 2,000 m (6,560 ft) in the east-northeast direction, and approximately 600 m thick (1,970 ft) with depths of 1,500 to 2,130 m (4,920 to 6,985 ft) below ground surface (Brown, 2003; RCC, 2013).

#### 4.2 Mining Method

The Resolution Copper Company is planning to use the underground panel cave mining method to extract ore from the deposit. This mining technique is a subset of the block cave mining method and similarly uses gravity and internal rock stresses to fragment, or break up, the ore as it is funneled through the draw-points at the extraction level. After initial capital costs of mine infrastructure and underground development, block cave mining is relatively low cost, enabling large, low-grade, deep ore bodies to be economically viable (RCC, 2013).

The panel caving method at RCC will have relatively high ore output. After the initial rampup period, RCC has scheduled an ore production rate of 120,000 tonnes per day and a maximum of approximately 150,000 tonnes per day (RCM, 2013). The planned extraction level, depending on final mine plan, may extend as deep as 2,200 m (7,215 ft) below ground surface and will have a herringbone crosscut pattern for the footprint (Brown, 2003; Resolution Copper Mining, 2013).

### 4.3 Discrete Fracture Network Generated from Borehole Data

• The comparative DFN analysis focused on the K<sub>vs</sub> unit for the following reasons: 1) it is the host rock for a substantial percentage of ore body, 2) it is the largest of the geological units present, and 3) it has one of the higher fracture intensities. The K<sub>vs</sub> unit was broken into five sub-domains through analysis of the fracture intensity (i.e., slope changes in the CFI plot in Figure 4.2) and based on the fracture orientations present (Figure 4.2). The K<sub>vs</sub> sub-domain intervals with the P<sub>10</sub> intensity values (approximate fracture spacing in parentheses), and three dominate discontinuity sets evaluated in FracMan with the Interactive Set Identification System (ISIS) feature (shown in dip/dip direction, in parentheses are the Terzaghi corrected fracture count, dispersion value and the reliability evaluated with Table 3.1, Table 3.2,

Table 3.3 from section 3.2.3: Fracture Intensity Comparison) are as follows:

- K<sub>vs1</sub>: 926.5 to 1029 m (3,039 to 3,375 ft) depth (Interval: 102.5 m (336 ft))
  - P<sub>10</sub> value of 1.48 m<sup>-1</sup> (0.45 ft<sup>-1</sup>) (0.68 m spacing (2.2 ft))
  - Discontinuity sets:
    - 69°/352° (count: 57, dispersion: 18, reliability: ±15%)
    - 56°/266° (count: 74, dispersion: 10, reliability: ±5%)
    - 42°/016° (count: 149, dispersion: 3, reliability: ±10%)
- K<sub>vs2</sub>: 1029 to 1094 m (3,375 to 3,588 ft) depth (interval: 65 m (213 ft))
  - $P_{10}$  value of 0.71 m<sup>-1</sup> (0.22 ft<sup>-1</sup>) (1.41 m spacing (4.6 ft))
  - Discontinuity sets:
    - 64°/358° (count: 10, dispersion: 85, reliability: ±20%)
    - 61°/289° (count: 43, dispersion: 13, reliability: ±10%)
    - 24°/088° (count: 28, dispersion: 4, reliability: ±20%)
- K<sub>vs3</sub>: 1094 to 1304.8 m (3,588 to 4,280 ft) depth (interval: 210.8 m (691 ft))
  - o P<sub>10</sub> value of 1.87 m<sup>-1</sup> (0.58 ft<sup>-1</sup>) (0.53 m spacing (1.7 ft))
  - o Discontinuity sets:
    - 66°/348° (count: 163, dispersion: 9, reliability: ±7%)
    - 60°/266° (count: 196, dispersion: 13, reliability: ±7%)
    - 24°/059° (count: 288, dispersion: 4, reliability: ±10%)
- K<sub>vs4</sub>: 1304.8 to 1593 m (4,280 to 5,225 ft) depth (interval: 288.2 m (945 ft))
  - o P<sub>10</sub> value of 1.15 m<sup>-1</sup> (0.35 ft<sup>-1</sup>) (0.87 m spacing (2.9 ft))
  - o Discontinuity sets:
    - 62°/052° (count: 227, dispersion: 6, reliability: ±10%)
    - 45°/298° (count: 229, dispersion: 3, reliability: ±10%)
    - 21°/141° (count: 83, dispersion: 29, reliability: ±5%)
- K<sub>vs5</sub>: 1593 to 1756 m (5,225 to 5,760 ft) depth (interval: 163 m (535 ft))
  - $P_{10}$  value of 0.61 m<sup>-1</sup> (0.19 ft<sup>-1</sup>) (1.6 m spacing (5.2 ft))

- o Discontinuity sets:
  - 45°/175° (count: 78, dispersion: 5, reliability: ±12%)
  - $74^{\circ}/273^{\circ}$  (count: 65, dispersion: 5, reliability:  $\pm 10\%$ )
  - 61°/077° (count: 45, dispersion: 8, reliability: ±15%)



**Figure 4.2** Cumulative fracture intensity (CFI) plot for the  $K_{vs}$  unit showing the five sub-domains and the corresponding contoured stereonet of the fracture poles.

The borehole location, gyro survey, and discontinuity data was imported into the FracMan program, and five separate model regions and borehole intervals were defined to match the evaluated  $K_{vs}$  sub-domains, shown in Figure 4.3. The borehole intervals were bootstrapped in the same manner as was done in the synthetic investigation in Chapter 3:. The P<sub>10</sub> scaling factor was defined as 1.0 for the five  $K_{vs}$  sub-domains because there were not two sub-

parallel discontinuity sets observed in the defined intervals (as recommended in Table 3.4 in section 3.3.2: P<sub>10</sub> Evaluation Findings).



**Figure 4.3** Methods used in the DFN and shaft comparative analysis with the five sub-domain intervals of the  $K_{vs}$  unit imported into FracMan and combined with the power law function (estimated from regional fractures and faults provided by Golder Associates).

The only difference in the bootstrap method used with the RES-008/-008A borehole as compared to the synthetic investigation models was the added use of a power law function to define the fracture size distribution for the fracture network generation. The power law function used was derived from regional fracture and fault traces, as shown in Figure 4.3. This information was provided by Dr. Steve Rogers from Golder Associates. Defining the fracture size distribution was ignored in the synthetic investigation models as fracture size (persistence) was assumed uniform for simplicity.

The power law distribution was modified through an iterative process for each sub-domain interval until the  $P_{10}$  intensity values were matched, as well as the calculated fracture area values were achieved for each of the  $K_{vs}$  sub-domains. A comparison borehole was placed in the model to sample the generated fracture network and verify that the sampled model network is similar to what was observed in the RES-008/-008A borehole, as shown in Figure 4.3. The CFI plot in Figure 4.4 shows the similarity of the model comparison borehole (gray line) and the five  $K_{vs}$  sub-domains (different colored lines for each interval). From the CFI plot, the generated fracture network intensity correlates very closely with the observed intensity in the borehole.



Figure 4.4 Cumulative Fracture Intensity (CFI) plot of the RCC RES-008/-008A and model comparison boreholes.

#### 4.4 Comparison of Resolution Shaft Data to the Model Shaft

### 4.4.1 Model Sampled with a Continuous Shaft

Once the iterative process was complete and the DFN model borehole was calibrated to the investigation borehole data, a continuous 10 m (30 ft) synthetic shaft was placed in the model. The location of the synthetic shaft in the model was set to follow the center coordinates of Shaft 10 using the NAD83-UTM27 Grid control points provided by RCC. This gave the synthetic shaft a similar spatial location relative to the model borehole as Shaft 10 and the RES-008/-008A borehole, as shown in Figure 4.5.



**Figure 4.5** The five sub-domains of the  $K_{vs}$  unit and the continuous synthetic shaft placed in the model at a similar location as Shaft 10 in relation to the borehole RES-008/-008A.

## 4.4.1.1 Intensity Comparison

The fractures intersecting the model shaft and forming traces along the exposed wall were sampled and compared to the Shaft 10 data using a CFI plot as shown in Figure 4.6. There was a total length of 353 m (1,160 ft) of discontinuity data for Shaft 10 provided for the  $K_{vs}$  unit (excluding the missing data gaps), compared to 829.5 m (2,720 ft) for RES-008/-008A borehole and continuous model shaft. The Shaft 10 data (black colored line) is shown with a solid line where the discontinuity data is continuous and there is high confidence in the calculated intensity values for the data gaps. Where the Shaft 10 data is shown with a dashed line, there are more gaps in the discontinuity data and the calculated intensity value is inferred (data gaps are greater than 50 percent of the defined interval). Where there were gaps in the Shaft 10 data greater than 10 m (30 ft), the line is not shown. The synthetic shaft is shown with the solid blue line.



Figure 4.6 Cumulative fracture intensity (CFI) plot of the RCC shaft 10 and synthetic model shaft.

From the visual comparison of the CFI plot, the model intensity correlates well with the observed intensity in Shaft 10. The larger sample window of the shaft (10 m (30 ft) diameter), compared to a borehole (RES-008: 14.0 cm (5.5 inches) diameter and RES-008A: 9.7 cm (3.8 inches) diameter), provides greater information on fracture intensity and potential changes in the intensity value of the sample population where the intensity appears constant in the sample line of a borehole. A change in fracture intensity is seen in Shaft 10 at an approximate depth of 1,450 to 1,560 m (4,755 to 5,115 ft) below ground surface in the Kvs unit compared to the DFN model. The steeper slope of the Shaft 10 black line, in the first 80 m (260 ft) of the observed change in fracture intensity (approximate depth of 1,450 to 1,530 m (4,755 to 5,015 ft) below ground surface in the model). The shallower slope of the CFI plot for the last 30 m (100 ft) of the observed change in fracture intensity (approximate depth of 1,530 to 1,560 m (5,015 to 5,115 ft) below ground surface in the model) indicates an increase in the fracture intensity of Shaft 10 compared to the model. For this interval, the observed intensity of the borehole was constant.

### 4.4.1.2 Fracture Size Distribution Comparison

The larger sample window of the shaft provides additional information on fracture size with the observed fracture trace length that is not possible with a borehole. The sampled trace length for the intersecting fractures on the continuous model shaft was compared to the Shaft 10 fracture trace length data is plotted with a fracture frequency and cumulative distribution function (CDF) for all of the  $K_{vs}$  data and the  $K_{vs}$  for sub-domain 4 data shown in Figure 4.7 and Figure 4.8, respectively. The  $K_{vs}$  sub-domain 4 was chosen for comparison, because: 1) the data set was relatively continuous with minimal data gaps, and 2) the intensity comparison was also very similar. The Shaft 10 data is shown with gray bars for the fracture frequency plot and a black line for the CDF plot; the model shaft is shown with a blue color for both of the plots.



**Figure 4.7** Fracture Frequency (shown with 1 m or 3.3 ft bins) and Cumulative Distribution Function (CDF) plots of the fracture trace lengths sampled from the shaft walls for all of the  $K_{vs}$  data.



**Figure 4.8** Fracture Frequency (shown in 1 m or 3.3 ft bins) and Cumulative Distribution Function (CDF) plots of the fracture trace lengths sampled from the shaft walls for the  $K_{vs}$  sub-domain 4 data.

Initial visual comparison of the CDF plots (Figure 4.7 and Figure 4.8), indicates that the model trace length distribution does not appear to match well with the observed trace lengths in Shaft 10 for all of the  $K_{vs}$  data, as well as for the  $K_{vs}$  sub-domain 4. The model shaft distribution curve has a distinct change at a trace length of 30 m (100 ft), giving an appearance of a bi-modal function for the underlying fracture size distribution. The fracture size distribution indicates a FPI on the shaft walls dominantly for fractures with a shallow dip. Therefore, the shallow dipping fractures that are 30 m (100 ft) (perfectly centered on the shaft) or greater in size are limited by the shaft diameter to be documented as 30 to 32 m (100 to 105 ft) trace length, which in-turn produces a higher percentage of 30 to 32 m (100 to 105 ft) fracture trace length. This is not observed in the Shaft 10 trace length distribution

where 99 percent of the provided fracture trace length is 10 m (30 ft) or less, showing an under-sampling of the intermediate fractures with trace lengths of 10 to 50 m.

The data was further analyzed with the Kolmogorov–Smirnov (K-S) statistical test ("Kolmogorov–Smirnov Test," 2016) to evaluate whether the Shaft 10 and model shaft fracture populations are from the same underlying distribution function. The K-S test was completed by sorting the data used in the Figure 4.7 and Figure 4.8 CDF plot curves into equal sized bins for the measured fracture trace length and counting the number of fractures for the respective bins. Several bin sizes (1 m, 5 m, and 10 m) were used to evaluate if there was sensitivity for the bin size used. The K-S test equations are shown below and the results are shown in Table 4.2.

$$D_{n,n'} = \sup_{x} \left| F_{1,n}(x) - F_{2,n'}(x) \right|$$

$$D_{Crit} = 1.36 \sqrt{\frac{n+n'}{nn'}}$$

The null hypothesis for the K-S test is that the two sample distributions come from the same empirical probability distribution. If  $D_{n,n'}$  is greater than  $D_{Crit}$ , the null hypothesis is rejected and the underlying distribution function is evaluated to be different for the two sample populations.

|                     | Bin Size | Bin Size Fracture Count |       | D i    | Date  | Null       |
|---------------------|----------|-------------------------|-------|--------|-------|------------|
|                     | (m (ft)) | Shaft 10                | Model | D'n,n' | DCrit | Hypothesis |
| All K <sub>vs</sub> | 1 (3.3)  | 8886                    | 3822  | 0.39   | 0.03  | Reject     |
|                     | 5 (15)   | 8886                    | 3822  | 0.35   | 0.03  | Reject     |
|                     | 10 (30)  | 8886                    | 3822  | 0.28   | 0.03  | Reject     |
| Sub-<br>domai       | 1 (3.3)  | 4556                    | 1143  | 0.41   | 0.05  | Reject     |
|                     | 5 (15)   | 4556                    | 1143  | 0.38   | 0.05  | Reject     |

 Table 4.2 Kolmogorov–Smirnov Test Results Comparing the Trace Length Distribution

 Functions of Shaft 10 and the Model Shaft

|  | 10 (30) | 4556 | 1143 | 0.29 | 0.05 | Reject |
|--|---------|------|------|------|------|--------|
|--|---------|------|------|------|------|--------|

The K-S test results indicate that the Shaft 10 and the model shaft have different trace length distribution functions. When the trace length data was evaluated in more detail, Shaft 10 dominantly sampled fractures inclined at  $45^{\circ}$  or greater (88 percent of the total sampled fractures). With the sampling method used for Shaft 10, i.e., photogrammetry analysis of individual 3 m (10 ft) lifts, inclined fractures would very likely cross into an adjacent shaft lift or a separate 3 m (10 ft) sample lift. Therefore, the inclined fracture trace length is limited by the shaft lift height and one long fracture will be counted multiple times with documented shorter trace length. The 3 m (10 ft) lift sampling method for Shaft 10 produces a higher percentage of 3 to 4.5 m (10 to 15 ft) fracture trace length than may be true of the continuous shaft walls.

Sampling the model with a continuous shaft, rather than multiple 3 m (10 ft) shaft lifts, has inherently produced different trace length distributions due to sampling. The next sections will further evaluate the trace length data and the sampling method to reduce comparison of different data sets due to sampling biases.

## 4.4.1.3 Fracture Size Distribution Comparison of Fractures with Dip Less than 20°

To overcome sampling discrepancy, fracture trace lengths sampled from Shaft 10 and the synthetic model shaft were filtered to evaluate fractures dipping  $20^{\circ}$  or less that potentially could be traced completely in one shaft lift without extending into the adjacent lift; i.e., with a FPI (one lift is 3 m or 10 ft in height). The sampled trace length for the intersecting fractures with a  $20^{\circ}$  dip or less are compared with a fracture frequency and CDF plots for all of the K<sub>vs</sub> data and the K<sub>vs</sub> for sub-domain 4 data shown in Figure 4.9 and Figure 4.10, respectively. The Shaft 10 data is shown with gray bars for the fracture frequency plot and a black line for the CDF plot; the synthetic model shaft is shown with the blue color for both of the plots.



**Figure 4.9** Fracture Frequency and Cumulative Distribution Function (CDF) plots of the fracture trace lengths sampled from the shaft walls for all of the  $K_{vs}$  data screened to fractures with a dip less than 20° with the potential to fit entirely within a 3 m (10 ft) high shaft lift.



**Figure 4.10** Fracture Frequency and Cumulative Distribution Function (CDF) plots of the fracture trace lengths sampled from the shaft walls for the  $K_{vs}$  sub-domain 4 data screened to fractures with a dip less than 20° with the potential to fit entirely within a 3 m (10 ft) high shaft lift.

From the initial visual comparison of the CDF plot of the fractures with a  $20^{\circ}$  dip or less (Figure 4.9 and Figure 4.10), indicate that the Shaft 10 and model shaft trace length distribution does not appear to correlate well. The FPI are still observed in the model shaft at a trace length of 30 m (100 ft), but are not documented in the Shaft 10 data where the trace length data is 7 m (23 ft) or less, showing an under-sampling of horizontal fractures and the intermediate fractures with trace lengths of 10 m or greater. Both of the CDF plots for all of the K<sub>vs</sub> data and K<sub>vs</sub> sub-domain 4 data are very similar visually, therefore, the data was further analyzed with the K-S test to evaluate whether the Shaft 10 and model shaft fracture populations are from the same underlying distribution function. The K-S test was completed using the same method previously described and the results are shown in Table 4.3.

|                                  | Bin Size | Fracture Count |       | D     | Der   | Null       |
|----------------------------------|----------|----------------|-------|-------|-------|------------|
|                                  | (m (ft)) | Shaft 10       | Model | Dn,n' | DCrit | Hypothesis |
| All K <sub>vs</sub>              | 1 (3.3)  | 67             | 415   | 0.35  | 0.18  | Reject     |
|                                  | 5 (15)   | 67             | 415   | 0.34  | 0.18  | Reject     |
|                                  | 10 (30)  | 67             | 415   | 0.31  | 0.18  | Reject     |
| K <sub>vs</sub> Sub-<br>domain 4 | 1 (3.3)  | 11             | 133   | 0.34  | 0.43  | Accept     |
|                                  | 5 (15)   | 11             | 133   | 0.26  | 0.43  | Accept     |
|                                  | 10 (30)  | 11             | 133   | 0.21  | 0.43  | Accept     |

 Table 4.3 Kolmogorov–Smirnov Test Results Comparing the Trace Length Distribution

 Functions for Fractures with 20° Dip or Less for Shaft 10 and the Model Shaft

The K-S test results indicate that the Shaft 10 and model shaft data have different trace length distribution functions when sampling all fractures dipping 20° or less for the K<sub>vs</sub> unit. However, the trace length distribution for K<sub>vs</sub> sub-domain 4 indicates the underlying distribution function is the same. From Table 4.3, the number of fractures with a 20° dip or less for Shaft 10 is significantly lower than the model shaft data. The approximate fracture intensity value and spacing calculated for the fractures dipping 20° dip or less are the following (missing data gaps accounted for):

- Fractures dipping 20° or less for the K<sub>vs</sub> unit:
  - o Shaft 10: 0.2  $m^{-1}$  (0.06 ft<sup>-1</sup>) (spacing of 5 m (15 ft))
  - Model shaft: 0.5 m<sup>-1</sup> (0.15 ft<sup>-1</sup>) (spacing 2 m (6.5 ft))
- Fractures dipping 20° or less for the K<sub>vs</sub> sub-domain 4:
  - o Shaft 10: 0.04 m<sup>-1</sup> (0.01 ft<sup>-1</sup>) (spacing of 25 m (80 ft))
  - o Model shaft:  $0.5 \text{ m}^{-1} (0.15 \text{ ft}^{-1}) (\text{spacing } 2 \text{ m} (6.5 \text{ ft}))$

The DFN modelled intensities matched well to the observed fracture frequency seen in RES-008/-008A (refer back to section 4.3: Discrete Fracture Network Generated from Borehole Data); the number of sub-horizontal fractures documented in Shaft 10 appears to undersample these fractures. This potential low count of sub-horizontal fractures could be due to: 1) photogrammetry sample bias with respect to shadowing of fracture surfaces due to the sample angle of the scanning equipment, 2) less concern for structural instability of sub-horizontal fractures creating a preferential bias toward sampling the sub-vertical fractures and under-sampling of sub-horizontal fractures, 3) blast damage obscuring fracture traces on the shaft wall, 4) vertical overburden pressure closing the fracture aperture diminishing the observed trace, or 5) a combination two or more of the above biases.

### 4.4.2 Model Sampled with 3 m or 10 ft Lift Shaft

To sample the DFN model in the same manner as Shaft 10, a portion of the model was sampled with 24 consecutive, 3 m (10ft) shaft lifts for a combined length of 72 m (235 ft). The chosen sample depth of 1,310 to 1,382 m below the ground surface (4,295 to 4,530 ft), with elevation of -40 to -112 m (-130 to -365 ft), was aligned with a continuously sampled section of Shaft 10 that correlated closely to the observed intensity comparison in section 4.4.1.1. The 3 m (10 ft) high, 10 m (30 ft) diameter synthetic shaft lifts were located in the model using the center coordinates of Shaft 10 (NAD83-UTM27 Grid control points) provided by RCC, giving the synthetic shaft a similar spatial location relative to the model borehole as Shaft 10 and the RES-008/-008A borehole, as shown in Figure 4.11.



**Figure 4.11** The five sub-domains of the Kvs unit and the 24 consecutive 3 m (10 ft) synthetic shaft lifts placed in the model at a similar location as Shaft 10 in relation to the borehole RES-008/-008A

# 4.4.2.1 Intensity Comparison

The fractures intersecting the model shaft and forming traces along the exposed wall were sampled with the 24 synthetic shaft lifts and compared to the Shaft 10 data using a CFI plot as shown in Figure 4.12. The Shaft 10 data (black colored line) is shown with a solid line where the discontinuity data is relatively continuous with few data gaps, a dashed line where there are large data gaps and the data is inferred (data gaps are greater than 50 percent of the

defined interval), and the line is not shown where the data gap is greater than 10 m (30 ft). The synthetic shaft lift data is shown with the solid blue line.



**Figure 4.12** Cumulative Fracture Intensity (CFI) plot of Shaft 10 and synthetic model shaft sampled with 3 m (10 ft) lifts.

From the visual comparison of the CFI plot, the model intensity correlates well with the observed intensity in Shaft 10 for this 72 m (235 ft) sample interval. The observed fracture intensity sampled in Shaft 10 and the model remains relatively constant with very similar slopes. This trend was observed with the continuous synthetic shaft sampling completed in section 4.4.1 (Model Sampled with a Continuous Shaft) and further verifies the DFN model.

### 4.4.2.2 Fracture Size Distribution Comparison

The DFN model was sampled with 24, 3 m (10 ft) high synthetic shaft lifts to collect trace length data on the fractures intersecting the shaft wall in a similar fashion as the trace length data was collected for Shaft 10. The fracture trace length data for the model shaft lifts were compared to the Shaft 10 data across the same interval with a fracture frequency and CDF plots shown in Figure 4.13. The Shaft 10 data is shown with gray bars and a black line; the model shaft is shown with a blue color for both. Figure 4.13 shows the data for the K<sub>vs</sub> unit sample interval depth of 1,310 to 1,382 m below ground surface (4,295 to 4,539 ft), with an elevation of -40 to -112 m (-130 to -365 ft). Figure 4.14 shows a fracture frequency and CDF plots for all of the Shaft 10 data for the selected interval and select model shaft data that had a trace length of 7 m (23 ft) or less. The fracture trace length selection of 7 m (23 ft) or less was chosen for comparison, because it was noted that for this interval, Shaft 10 did not have fracture trace length greater than 7 m (23 ft). This was also seen for the fractures dipping 20° or less in the K<sub>vs</sub> sub-domain 4 (Section 4.4.1.3: Fracture Size Distribution Comparison of Fractures with Dip Less than 20°).



**Figure 4.13** Fracture Frequency and Cumulative Distribution Function (CDF) plots of fracture trace lengths on shaft walls for the  $K_{vs}$  unit for the depth interval of 1,310 to 1,382 m (4,295 to 4,530 ft), with an elevation of -40 to -112 m (-130 to -365 ft).



**Figure 4.14** Fracture Frequency and Cumulative Distribution Function (CDF) plots of fracture trace lengths on shaft walls for the  $K_{vs}$  data with a trace length 7m (23 ft) or less for the depth interval of 1,310 to 1,382 m (4,295 to 4,530 ft), with an elevation of -40 to -112 m (-130 to -365 ft).

From the initial visual comparison of the CDF plots (Figure 4.13 and Figure 4.14), the model trace length distribution does not appear to match well with the observed trace lengths in Shaft 10 for all of the data in the  $K_{vs}$  interval, but is much closer for the selected model trace lengths of 7 m (23 ft) or less, but Shaft 10 still shows a greater number of shorter sampled fracture trace length than the model shaft has sampled. The data was analyzed with K-S test to evaluate whether the Shaft 10 and model shaft fracture populations are from the same underlying distribution function. The K-S test was completed by dividing Figure 4.13 CDF plots curves into equal bin sizes of 1 m, 5 m, and 10 m (3.3 ft, 15 ft, 30 ft). The K-S test results are shown in Table 4.4.

|                  | Bin Size Fracture Count |          | D     | Dai   | Null |            |
|------------------|-------------------------|----------|-------|-------|------|------------|
|                  | (m (ft))                | Shaft 10 | Model | Dn,n' | DCnt | Hypothesis |
| All<br>Fractures | 1 (3.3)                 | 1426     | 818   | 0.52  | 0.06 | Reject     |
|                  | 5 (15)                  | 1426     | 818   | 0.46  | 0.06 | Reject     |
|                  | 10 (30)                 | 1426     | 818   | 0.37  | 0.06 | Reject     |
| <7 m<br>(<23 ft) | 1 (3.3)                 | 1426     | 277   | 0.34  | 0.07 | Reject     |

**Table 4.4** Kolmogorov–Smirnov Test Results Comparing the Trace Length Distribution

 Functions for Fractures for Shaft 10 and the Model Shaft sampled with 3 m (10 ft) Lifts

The K-S test results indicate the Shaft 10 and the model shaft have different underlying trace length distribution functions, even with the model interval being sampled in the same manner as Shaft 10 with 3 m (10 ft) lifts. Shaft 10 continues to sample significantly more (approximately 1.75 times) fractures than the model shaft as shown in the fracture count column in Table 4.4.

To better understand what type of fractures (sub-horizontal, inclined, or sub-vertical) and the number of fractures Shaft 10 is sampling compared to the model, a cumulative distribution plot for the fracture dip was produced (Figure 4.15). The Shaft 10 data is shown with the black line, the model shaft sampled with 3 m (10 ft) lifts is shown with a red line, and for comparison the model sampled with a continuous shaft is shown with the blue line and the RES-008/-008A borehole is shown with a gray line.



Figure 4.15 Cumulative fracture dip distribution plot

From Figure 4.15, the slope of Shaft 10 is very close (less than 3 percent difference) to the slope of the 3 m (10 ft) lift-model line for fractures dipping 30° to 70° (inclined fractures). For the sub-horizontal fractures, there are very few sampled in Shaft 10 (previously noted in section 4.4.1.3: Fracture Size Distribution Comparison of Fractures with Dip Less than 20°). Shaft 10 sampled less than 3 percent of the total for the sub-horizontal fractures (dipping 30° or less); where the 3 m (10 ft) lift model shaft sampled a total of almost 18 percent.

The sub-vertical fractures show almost the opposite trend as the sampled sub-horizontal fractures. Shaft 10 sampled a total of almost 46 percent of the total for the sub-vertical fractures (dipping  $70^{\circ}$  or more); where the 3 m (10 ft) lift model shaft sampled a total of 23

percent. The difference is even more drastic for the sampled fractures with a dip of 80° or more with Shaft 10 sampling three times the number of fractures than the model shaft.

The greater percentage of sub-vertical fractures observed in Shaft 10 could be due to greater length of the fracture size (fractures extend beyond two lifts for one fracture) than compared to the generated DFN (where the majority of the sampled fractures only extended into one adjacent lift, approximately 95%). However, these longer trace lengths are not observed with the shallower dipping fractures where the maximum trace lengths are 7 m (23 ft). This could be due to: 1) photogrammetry sample bias with respect to shadowing of fracture surfaces due to the sample angle of the scanning equipment, 2) different fracture size distribution functions for the sub-vertical fractures compared to the sub-horizontal, 3) potential undersampling of perceived non-critical, sub-horizontal fractures due to sample bias creating distribution differences that may not be correct, 4) potential over-sampling of perceived that may not be correct, 5) blast damage could obscure fracture traces and/ or increase the fracture intensity on the shaft wall by being incorrectly documented as fractures, 5) vertical overburden pressure closing the fracture aperture diminishing the observed trace of sub-horizontal discontinuities, or 6) a combination of two or more of the above biases.

The model shaft that sampled the DFN with a continuous shaft (blue line on Figure 4.15) is included on the figure to show how the fracture distribution will shift or change with the sampling method and matches closely to the fracture distribution observed in the RES-008/-008A borehole (gray line in Figure 4.15). The model sampled with 3 m (10 ft) lifts does show an increase in sampling for fractures inclined 50° to 80° with the shallower slope in the line. This shift would also be expected for Shaft 10 if the fractures that cross into an adjacent lift were combined into a single fracture; thereby, shifting the Shaft 10 line to the right in the plot.

### 4.5 Findings from Borehole to Shaft Comparison

The DFN model generated from the exploration borehole (RES-008/-008A) and mapping of regional fractures and faults produced a fracture network that correlated well with the

observed fracture intensity of the shaft. This method of using regional mapped faults and fractures to aid in defining the initial fracture size distribution at depth has proven to produce a high quality preliminary DFN model when calibrated and constrained by data at depth derived from borehole information.

Detailed analysis of the discontinuity trace length distributions indicate the generated model is different than observations made with Shaft 10. However, there are several epistemic uncertainties with potential selective and/or biased sampling for the Shaft 10 data and include the following:

- Potential under-sampling of sub-horizontal fractures:
  - Vertical stress decreasing or completely closing the aperture of the discontinuity, substantially reducing the trace visibility.
  - o Photogrammetry biasing due to fracture surfaces angles.
  - o Human bias overlooking fractured viewed as non-critical.
  - o Potential blast damage eliminating fractures.
- Over sampling of sub-vertical fractures:
  - Vertical stress increasing the aperture or further propagation of a discontinuity with stress reduction at the excavation face, increasing the trace visibility.
  - Fractures documented in multiple lifts.
  - Human bias focusing on fractured viewed as critical.
  - o Potential blast damage mistaken as fractures.

The potential under-sampling of sub-horizontal fractures and over-sampling the sub-vertical fractures provide an inaccurate discontinuity size distribution that would not aid in further constraints with respect to the fracture size at depth. It is important to correct these biases to provide an accurate comparison and produce a better, more accurate DFN representation of the rock mass in the future model iterations.

Corrected shaft discontinuity data would aid in the verification and improvement of the model fit; however, the intervals in the shaft where large amounts of data are missing or not collected contribute to increased epistemic uncertainty for those model intervals. The continuous collection of complete, unbiased discontinuity data from all shaft and adit workings associated with the RCC project site would be of significant value for future iterations of DFN modeling for use in stability analyses and to support design of the mine infrastructure, cave propagation modeling, block size distributions and expected fragmentation at the draw points.

# **Chapter 5: Conclusion and Future Work**

## 5.1 Synthetic Borehole Investigation

The synthetic borehole investigations involved utilization of a synthetic data set in which a DFN is seeded with known characteristics to generate a baseline fracture network. A borehole investigation was then simulated to collect observed fracture data from the baseline model, which was subsequently used to generate multiple DFN realizations. The generated DFN models were compared to the baseline DFN as a measure of similarity (or the representativeness). Three synthetic borehole investigation models were used to assess the impact on borehole data collection in a single geological domain with respect to the borehole spatial location, orientation, and intensity of fractures encountered.

Comparison of the baseline and generated fracture networks from the three synthetic borehole investigation setups provided guidelines for optimizing feasibility-level drilling investigations. These showed where there were diminishing returns related to the quality and quantity of data collected and the resulting reliability of DFN models produced. It is critical to understand how representative a DFN model is, as well as the limitations of the model, based on the source, quantity, and quality of the data. The key findings for the synthetic borehole investigations are the following:

- The mean orientation for discontinuity sets derived from borehole investigations are well represented by DFN modeling; their reliability does not appear to be dependent on the length or spatial distribution of the boreholes within a single geological domain.
- The dispersion and intensity of a discontinuity set derived from borehole investigations are dependent on the length and/or the spatial distribution of the boreholes.
  - To maintain a project budget total drill length, the addition of more boreholes will not necessarily improve the accuracy of inferred spatial data for DFN purposes; especially where splitting a longer borehole into multiple boreholes will substantially reduce the individual borehole length. This is particularly <sup>96</sup>

true where sub-parallel discontinuities, with respect to the borehole, are present as shorter boreholes will not pick up the full distribution characteristics of the discontinuity set.

- However, if the boreholes are relatively similar in length and there is not a cost to the project budget total drill length, slightly reducing the length of multiple boreholes to add one or more boreholes to an investigation may improve the accuracy of inferred spatial data for DFN purposes.
- Accordingly, drilling fewer boreholes with greater lengths may improve the reliability of the evaluated discontinuity set distribution characteristics, with added economic benefits.
- The findings listed above are specific to data collection for DFN modelling purposes. Where the investigation objectives include identifying multiple domains and determining geologic boundaries, more shorter-length boreholes may prove to be a better strategy than fewer longer-length boreholes.
- The borehole angle and orientation has a significant impact on the reliability of the DFN derived from the collected data.
  - It is important to incrementally improve knowledge of the fracture network with each borehole. Subsequent decisions regarding the next borehole's orientation (inclination angle and direction) should be optimized relative to the target discontinuity sets to maximizing the quantity, quality, and reliability of the sampled data.
  - Multiple oriented boreholes provide a more complete and reliable understanding of the fracture network.
- Inclined boreholes are not always better and depend on the orientation of the discontinuity sets present; boreholes that are sub-parallel to a discontinuity set may shadow or miss the discontinuity set completely within the blind zone of the borehole.
  - To reduce or avoid the borehole blind zones, it is recommended that during an investigation drilling campaign, the first borehole should be quickly analyzed

before proceeding to determine the best inclination angle and direction of subsequent boreholes.

- Approximately 50 to 100 data points (with the Terzaghi correction applied) are required to adequately characterize a discontinuity set orientation distribution with respect to the dispersion parameter.
  - The angle between the discontinuity set and borehole is sensitive to the quantity of fractures sampled with respect to evaluating the dispersion distribution with the following trends:
    - Increasing sampled fractures from 50 to 100 will potentially reduce the error to 5-10 percent depending on the angle between the discontinuity and borehole.
    - Increasing accuracy with higher dispersion values and fewer sampled fractures are required.

The central objective of the synthetic borehole investigation research was to investigate improved means to forecast rock mass discontinuity geometric distribution characteristics (orientation and intensity) with sample data limited to boreholes and the reliability of the subsequent DFN modeling with the obtained discontinuity data. Even with the limitation of discontinuity data sampled with boreholes, it is critical to DFN modeling that the discontinuity data set is robust and able to characterize the distribution characteristics; thereby, the site knowledge can progress from epistemic uncertainty (lack of knowledge) toward aleatory variability (characterization of the natural randomness of the discontinuity distributions), which is required for stochastic DFN modeling.

## 5.2 Findings from the P<sub>10</sub> Evaluation

Through the synthetic borehole investigations, it was observed that the generated fracture network had a lower intensity (or the fracture network was less dense) than the baseline fracture network when the discontinuity sets were sub-parallel to the borehole(s), even with the Terzaghi correction factor applied to the bootstrap method available in FracMan. To better understand how the discontinuity sets were affected when using the bootstrap process

used within FracMan, the synthetic borehole investigation models were modified to evaluate a scaling factor for the bootstrap method.

From the  $P_{10}$  scaling factor evaluation, it was observed that the angle between the discontinuity set and the borehole did impact the subsequent DFN generation. For the bootstrap method, the evaluated scaling factors for the  $P_{10}$  parameter are shown in Table 3.4 in section 3.3.2:  $P_{10}$  Evaluation Findings and are summarized below:

- The P<sub>10</sub> scaling factor ranged from 1.0 to 1.15.
- The P<sub>10</sub> scaling factor is dependent on the number of discontinuity sets that are subparallel to the borehole (20° or less), and the average angle, in degrees, between the discontinuity set and the borehole.
- The use of the P<sub>10</sub> scaling factor is recommended with the following considerations:
  - The fracture network should consist of three discontinuity sets.
  - Two of the three sets should be sub-parallel to the borehole.
  - Used in conjunction with the Terzaghi correction factor.
  - The factor is applied to all discontinuity sets, and not just to the sub-parallel discontinuity sets.
  - With multiple boreholes, the P<sub>10</sub> scaling factor should only be used if the boreholes all have the same orientation or similar angles with respect to the discontinuity sets.

The  $P_{10}$  scaling factor may improve the accuracy of the discontinuity set intensity, and thereby the accuracy of the fracture network density, which is critical to the representativeness of the generated DFN model. The discontinuity set intensity is important for analysis of the in situ fragmentation or block size distribution that can be expected and the fracture connectivity that will directly affect the rock mass strength, stability and hydraulic flow.

### 5.3 Findings from Borehole to Shaft Comparison

The analysis and DFN modeling of discontinuity data provided by RCC from their Resolution Mine project in Arizona, USA, utilized discontinuity data derived from core logging and downhole televiewer data of a deep geotechnical borehole (RES-008 and RES-008A, telescoped borehole); and discontinuity data derived from photogrammetry data of a co-located deep shaft (Shaft 10). A DFN model was produced with the borehole data and subsequently sampled with a synthetic shaft. The discontinuity traces sampled with the synthetic shaft were compared to the RCC Shaft 10 photogrammetry data to evaluate the reliability of discontinuity size distributions between those observed at depth in the excavated shaft and those represented in the DFN model.

The objective of the research on borehole to shaft scaling comparison was to investigate improved means to forecast rock mass discontinuity geometric characteristics (orientation, intensity, and persistence) across different scales (borehole with 0.063 m or 0.2 ft versus shaft with 10 m or 30 ft respective diameters). The larger exposure scale of the shaft, compared to the borehole, provided a means to focus on the discontinuity persistence, which is a well-known and challenging parameter to fully characterize. This allowed the evaluation of a current method of modeling discontinuity size distributions to be assessed and whether the model adequately represents the persistence of discontinuity trace lengths observed in the excavated shaft at depth. The method used in defining the required persistence parameter for the DFN site model utilized regional mapped faults and fractures with small scale fractures to evaluate a power-law distribution for the discontinuity size distribution. The key findings for the DFN model using the RES-008/-008A borehole data and a power-law distribution to define to discontinuity size are the following:

• The method of defining the discontinuity size distribution using a power-law distribution evaluated with regional faults and fractures has proven to produce a high quality preliminary DFN model when calibrated and constrained by data at depth derived from the RES-008/-008A borehole information.

- Detailed analyses of the discontinuity trace length distributions indicate several epistemic uncertainties with potential selective and/or biased sampling for Shaft 10 data, which include:
  - Potential under-sampling of sub-horizontal fractures due to the following:
    - Vertical stress decreasing or completely closing the aperture of the discontinuity, substantially reducing the trace visibility.
    - Photogrammetry biasing due to fracture surfaces angles.
    - Human bias overlooking fractured viewed as non-critical.
    - Potential blast damage eliminating fractures.
  - Potential over-sampling of sub-vertical fractures due to the following:
    - Vertical stress increasing the aperture or further propagation of a discontinuity with stress reduction at the excavation face, increasing the trace visibility.
    - Fractures documented in multiple lifts.
    - Human bias focusing on fractured viewed as critical.
    - Potential blast damage mistaken as fractures.

Corrected shaft discontinuity data, with respect to trace length distributions, would aid in the further verification and improvement of the representativeness of the site model to observations made at depth in the shaft. Accordingly, the intervals in the shaft where large amounts of data are missing or not collected, contribute to increased uncertainties for those model intervals. The continuous collection of quality discontinuity data from all underground excavations (shaft and adit workings) associated with RCC project site would be of significant value for future iterations of DFN modeling for use in stability analyses and support design of the mine infrastructure, cave propagation modeling, in situ block size distributions and expected fragmentation at the draw points.

## 5.4 Future Research

The potential biased sampling of sub-horizontal and sub-vertical fracture traces observed on the excavated shaft walls provide an inaccurate fracture size distribution that currently would not aid in further constraints for evaluation of the discontinuity size distribution at depth. Review of the photogrammetry analysis for additional shallow dipping discontinuities and potential mistaken blast damage is recommended to be sure the discontinuity trace length data is objectively comprehensive and unbiased.

Incorporation of the nuclear waste industry practice in evaluation of intermediate structure size with the FPI criteria could provide a beneficial parameter in the evaluation of discontinuities with potential fault slip behavior and expanding the FPI criteria across multiple lifts with combining trace observations of sub-vertical discontinuities that currently are documented more than once. The combining of multiple sub-vertical discontinuity trace length measurements would also reduce the truncation bias currently imposed sample data. Obtaining corrected trace length data would aid in the evaluation of the discontinuity size distribution and the maximum discontinuity expected in the rock mass, as well as the mine footprint.

It is important to correct these biases to provide an accurate comparison between DFN models and excavation observations, and continue to produce improved DFN representation of the rock mass with future model iterations as additional information is collected with underground construction. This will move the feasibility-level epistemic uncertainty further towards aleatory variability for the site data, which is required for stochastic DFN modeling. This would also aid in the evaluation of the sub-horizontal and sub-vertical discontinuity sets and whether they have the same or similar size distributions.

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#### **Appendix A Borehole Spatial Comparison Plots**

#### A.1 Summary Plots

The following summary plots show the average calculated comparison of the Generated Network parameters compared to the Baseline Network parameters. The average was evaluated from the output of the twenty-five (25) runs for each of the synthetic borehole spatial investigations and shown in the box and whisker plots in Appendix A.2. The parameter comparison equations used are the following:

P<sub>10</sub> and Dispersion values comparison calculated with:

$$-\left|1-\frac{GNW}{BNW}\right|$$

Dip and Dip Direction values comparison calculated with:

$$-\left|\frac{(GNW-BNW)}{30}\right|$$

where: GNW = Generated Network

BNW = Baseline Network

The average parameter comparison for the four parameters, across the dispersion values of 5, 20, and 80, were then scaled using the following equation:

$$Scaling = \frac{(x - \min.)}{(max. - min.)}$$

#### A.1.1 Inclined Network Summary Plots

Network Comparison - Boreholes with Decreasing Length Dispersion: 5 Dispersion: 20 **Dispersion: 80** 



**Inclined Joint Network** 

# A.1.2 Vertical-Horizontal Network Summary Plots

Dispersion: 5 **Dispersion: 20 Dispersion: 80** 1 1 Joint Set 15°/295° (D/DD) 0.8 0.8 Scaled (0,1) 0.6 0.6 0.4 0.4 0.2 0.2 5/1 2 3 2 5/14 1 4 3 4 2 3 5 1 1 Joint Set 80°/070° (D/DD) 0.8 0.8 Scaled (0,1) 0.6 0.4 0.4 0.2 0.2 2 5/1 2 3 4 5/1 3 4 2 3 4 5 1 1 1 **Joint Set 80°/160° (D/DD)** Scaled (0,1) 0.8 0.8 0.6 0.6 0.4 0.4 LEGEND Dip Dip Dir. No. Fractures Dispersion 0.2 0.2 2 3 4 Number of Boreholes 2 3 5/1 5/1 3 4 2 1 4 5

Vertical-Horizontal Joint Network

Network Comparison - Boreholes with Decreasing Length

- A.2 Box and Whisker Plots for the Borehole Spatial Comparison Analysis
- A.2.3 Comparison of Generated Network to the Inclined Baseline Network



Inclined Joint Network



Inclined Joint Network



Inclined Joint Network Network Comparison - Boreholes with Decreasing Length (Dip Direction Parameter Comparison)



Inclinded Joint Network Network Comparison - Boreholes with Decreasing Length (Dispersion Parameter Comparison)

# A.2.4 Comparison of Generated Network to the Vertical-Horizontal Baseline Network



Vertical-Horizontal Joint Network Network Comparison - Boreholes with Decreasing Length (Fracture Intensity Parameter Comparison)



## Vertical-Horizontal Joint Network



Vertical-Horizontal Joint Network Network Comparison - Boreholes with Decreasing Length (Dip Direction Parameter Comparison)



<u>Vertical-Horizontal Joint Network</u> Network Comparison - Boreholes with Decreasing Length (Dispersion Parameter Comparison)

#### **Appendix B** Borehole Orientation Comparison Plots

#### **B.1** Summary Plots

The following summary plots show the average calculated comparison of the Generated Network parameters compared to the Baseline Network parameters. The average was evaluated from the output of the twenty-five (25) runs for each of the synthetic borehole orientation investigations and shown in the box and whisker plots in Appendix B.2. The parameter comparison equations used are the following:

P<sub>10</sub> and Dispersion values comparison calculated with:

$$-\left|1-\frac{GNW}{BNW}\right|$$

Dip and Dip Direction values comparison calculated with:

$$-\left|\frac{(GNW-BNW)}{30}\right|$$

where: GNW = Generated Network

BNW = Baseline Network

The average parameter comparison for the four parameters, across the dispersion values of 5, 20, and 80, were then scaled using the following equation:

$$Scaling = \frac{(x - \min.)}{(max. - min.)}$$

#### **B.1.1 Inclined Network Summary Plots**

Inclined Joint Network Network Comparison with 90° Angled Boreholes



Inclined Joint Network Network Comparison with 70° Angled Boreholes



Inclined Joint Network Network Comparison with 55° Angled Boreholes



# **B.1.2** Vertical-Horizontal Network Summary Plots

Vertical-Horizontal Joint Network

Network Comparison with 90° Angled Boreholes



Dispersion: 5 **Dispersion: 20 Dispersion: 80** - 1 Joint Set 15°/295° (D/DD) 0.8 0.8 Scaled (0,1) 0.6 0.6 0.4 0.4 0.2 - 0.2 9/1 9/1 б Joint Set 80°/070° (D/DD) 0.8 0.8 Scaled (0,1) 0.6 0.6 0.4 0.4 0.2 0.2 9/1 9/1 б 8.0 0.6 0.4 0.2 LEGEND Dip No. Fractures Dip Dir. Disp. 9/1 9/1 б б Number of Boreholes

### Vertical-Horizontal Joint Network

Network Comparison with 70° Angled Boreholes

Vertical-Horizontal Joint Network

Network Comparison with 55° Angled Boreholes



- **B.2** Box and Whisker Plots for the Borehole Orientation Comparison Analysis
- **B.2.3** Comparison of Generated Network to the Inclined Baseline Network



<sup>.</sup> 



Inclined Joint Network Network Comparison - Joint Set 45°/025° (D/DD)





Inclined Joint Network Network Comparison - Joint Set 45°/205° (D/DD) (Dip Parameter Comparison)



Inclined Joint Network Network Comparison - Joint Set 45°/025° (D/DD) (Dip Parameter Comparison)



Inclined Joint Network Network Comparison - Joint Set 45°/115° (D/DD) (Dip Parameter Comparison)



**Inclined Joint Network** 

Network Comparison - Joint Set 45°/205° (D/DD)

(Dip Direction Parameter Comparison)



Inclined Joint Network Network Comparison - Joint Set 45°/025° (D/DD)

(Dip Direction Parameter Comparison)




Inclined Joint Network Network Comparison - Joint Set 45°/205° (D/DD)



Inclined Joint Network Network Comparison - Joint Set 45°/025° (D/DD) (Dispersion Parameter Comparison)



Inclinded Joint Network Network Comparison - Joint Set 45°/115° (D/DD)

**B.2.4** Comparison of Generated Network to the Vertical-Horizontal Baseline Network



<sup>&</sup>lt;u>Vertical-Horizontal Joint Network</u> Network Comparison - Joint Set 15°/295° (D/DD)

(Fracture Intensity Parameter Comparison)



Vertical-Horizontal Joint Network

<sup>135</sup> 





Vertical-Horizontal Joint Network Network Comparison - Joint Set 15°/295° (D/DD) (Dip Parameter Comparison)



<u>Vertical-Horizontal Joint Network</u> Network Comparison - Joint Set 80°/070° (D/DD)



Vertical-Horizontal Joint Network Network Comparison - Joint Set 80°/160° (D/DD)



<u>Vertical-Horizontal Joint Network</u> Network Comparison - Joint Set 15°/295° (D/DD)









Vertical-Horizontal Joint Network



<u>Vertical-Horizontal Joint Network</u> Network Comparison - Joint Set 80°/160° (D/DD)

#### Appendix C Fracture Intensity Comparison Plots

- C.1 Summary Plots for the Fracture Intensity Comparison Analysis
- C.1.1 Discontinuity Sets Modelled Individually Summary Plot



# C.1.2 Discontinuity Sets Modelled as One Network Summary Plot





### C.2 Box and Whisker Plots for the Fracture Intensity Comparison Analysis

# C.2.3 Discontinuity Sets Modelled Individually









# C.2.4 Discontinuity Sets Modelled as One Network









### Appendix D P<sub>10</sub> Scaling Factor Plots

- **D.1** Box and Whisker Plots for the Orthogonal Network
- D.1.1 45' Angle between the Discontinuity Sets and the Borehole






























D.1.2 27.5 Angle between the Discontinuity Sets and the Borehole































D.1.3 19<sup>•</sup> Angle between the Discontinuity Sets and the Borehole






























D.1.4 14.5 Angle between the Discontinuity Sets and the Borehole































**D.1.5** 10<sup>•</sup> Angle between the Discontinuity Sets and the Borehole







Scaling of P<sub>10</sub> with 1 Boreholes Orthogonal Horizontal-Vertical Network: Dispersion 80











Scaling of P<sub>10</sub> with 3 Boreholes Orthogonal Horizontal-Vertical Network: Dispersion 20














## **D.2** Box and Whisker Plots for the Conjugate Network

## D.2.6 45' Angle between the Discontinuity Sets and the Borehole































D.2.7 27.5 Angle between the Discontinuity Sets and the Borehole































D.2.8 19<sup>•</sup> Angle between the Discontinuity Sets and the Borehole






























## **D.2.9** 14.5<sup>•</sup> Angle between the Discontinuity Sets and the Borehole































**D.2.10 10 Angle between the Discontinuity Sets and the Borehole** 




























