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Review

DFN: An Emerging Tool for Stochastic Modelling and Geomechanical Design

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Abstract: The discrete fracture networks (DFN) have become indispensable tools for geomechanical modelling of jointed rock masses. The technology creates a three-dimensional (3D) representation of fracture geometry used in the construction of surface and subsurface engineering projects in mining, civil engineering, and fracturing of the reservoir in the oil and gas industry. The approach depends on the accuracy of the data obtained during site investigation to create models that represent the fracture geometry of the structure. The better the acquired information available, the better the stochastic analysis that determines the engineering applications and designs that can be carried out. Therefore, it is important to use instruments that can capture fracture distribution characteristics such as fracture intensity, fracture orientation, spatial distribution, fracture length, fracture aperture, and size. This study provides a detailed review of the recent advances in the application of a DFN for modelling jointed rock masses in different engineering applications. The paper shows the principles of modelling in a DFN, including various data-capturing methodologies, and the general application of DFN in various fields. Several case studies where the DFN method was applied are presented in the paper. These include evaluation of slope in an open pit mine, modelling of discontinuity in tunneling, stability evaluation of coal seam longwall, the design of high-level radioactive waste, prediction of groundwater flow, fracturing of petroleum reservoirs, and geothermal cracking of shale gas in the coal bed. However, despite the versatility of the DFN technique, there are still some limitations and challenges to the integration of complexities encountered in rock masses within DFN models.

Keywords: discrete fracture network; 3D laser scanner; fracture geometry; numerical modelling; hydraulic fracturing

Citation: Kolapo, P.; Ogunsola, N.O.; Munemo, P.; Alewi, D.; Komolafe, K.; Giwa-Bioku, A. DFN: An Emerging Tool for Stochastic Modelling and Geomechanical Design. *Eng* **2023**, *4*, 174–205. https://doi.org/10.3390/eng4010011

Academic Editors: Reza Rezaee and Yujie Yuan

Received: 25 November 2022
Revised: 29 December 2022
Accepted: 30 December 2022
Published: 5 January 2023

1. Introduction

Numerical modelling of rocks begins with setting up a model that is a representation of a rock mass and can be investigated to predict its behaviour upon being subjected to several external conditions. However, rock masses are rarely intact but contain discontinuities such as joints, faults, and bedding planes which affect their mechanical behaviour. When modelling rock masses, it is critical to incorporate the inherent complex discontinuities. Discrete fracture network (DFN) models have proved to be versatile in numerical simulation of such discontinuities, in that they explicitly capture the discontinuity properties and fracture geometries. The concept of the DFN involves the mathematical modelling of fracture sets which represent the discontinuities' network structure in a real rock mass.

Crustal rocks are the fundamental building blocks of the earth's crust and are important to the successful implementation and construction of many surface and subsurface engineering structures, including nuclear waste repositories, enhanced oil recovery, enhanced geothermal energy systems, and other underground structures. However, these surface and subsurface rock masses are characterized by a network of complex geological structures (fractures), including faults, bedding planes, unconformities, joints, etc. Accurate characterization of the variability and distribution of these fracture systems is essential to the optimal functioning of these constructed engineering structures. A discrete fracture network (DFN) is one of the numerical modelling approaches used to describe joint properties and variability in a rock mass based on available data from mapping techniques such as the laser scanning technique, geophysical mapping, borehole mapping, and photogrammetry technology. The DFN method presents a realistic three-dimensional (3D) geometry, joint properties, and the variation in the joint fracture system within a rock mass based on the acquired data. DFN modelling specifically defines the geometrical properties of an individual fracture and the topological relationship between the rock fracture such as joints, faults, veins, and bedding planes [1]. The development of DFN models requires sourcing and integrating into a unit of a vast amount of fracture network data from both surface and underground bedrocks [2]. The DFN software generates the 3D representation of fractures by making use of the fractures' characteristics, such as size and orientation, which are treated as random variables with given probability distributions. The development of the DFN model is categorized into four main components, namely the consistent structural and stratigraphic model, integrating fracture characterization, static DFN model construction, and DFN dynamic validation and upscaling.

However, collecting fracture data seems a herculean task, particularly at several kilometres below the Earth's crust. Even with continuous advancements in technology, the bulk of high-resolution observations of fracture patterns is still restricted to surface mapping and borehole measurements, which raises difficulties with under-sampling and stereotyping [3]. A DFN model is basically a statistical ensemble, and because it is challenging to collect data underground, most DFNs rely on statistics of fracture networks, and it was anticipated that the target site will be a manifestation of this statistical ensemble [4]. The result of the DFN approach serves as advanced tools in mining operations and other engineering projects such as dam construction, underground excavations, caverns, tunneling, design of underground support systems, fragmentation analysis in blasting [5], and fluid flow in a rock mass. Similarly, DFNs are extensively used in the oil and gas industry to predict the hydraulic behaviour and fracture connectivity in a rock mass [6]. The hydraulic behaviour and fracture parameters are used to establish the zones with high pore pressure during the construction work such as underground hydrocarbon reservoirs and nuclear waste. The DFN is not a novel technology, and the use of the DFN numerical approach can be traced to the early 1970s when it was used to characterize and model fluid percolation in natural fractures [7]. It was adopted and gained wider practice in the mineral extraction industry, most especially in rock engineering and rock mechanics professions. It has also been widely used in geological engineering and hydrogeological and petroleum applications. Currently, the DFN is an integral tool used in various studies and engineering designs for several civil and mining projects [8]. For instance, the DFN can be a useful tool for an in-depth analysis of rock mass strength in a jointed rock mass. It is predominantly used in a rock mass with the presence of discontinuities or highly fractured rock mass.

This study thus aims at reviewing the recent advances in the application of the DFN for modelling jointed rock masses in different engineering applications. The purpose is to catalogue all the principles of modelling in the DFN, including various data-capturing methodologies, different computer programming codes for DFN generation, and the general application of the DFN in various fields, and some specific case studies of DFN models in different engineering applications are elicited. Following that, the observed challenges with the already developed DFN models were pinpointed with the aim of offering purposeful solutions. The review concluded by outlining future research directions in this field. It is, however, pertinent to note that this review is not totally comprehensive on the subject matter, and for the sake of concision, just a small number of credible sources are referenced. For a comprehensive review on specific studies of coupled hydromechanical (HM) characteristics of fractured rocks using the DFN, readers are directed to consult the reviews by [1,9].

2. Background Study

2.1. Overview of Discrete Fracture Network in Mining

There has been an increase in the use of the DFN in providing solutions to mining and geotechnical engineering problems. DFN models have proven to be an effective technology for rock masses characterization using statistical distribution to represent the fracture network [10]. The availability of high computing technologies (hardware and software) has increased the performance of the DFN serving as one of the most versatile tools for analyzing complicated rock mass states and interactions of the fracture network [11].

The method produces a 3D representation of the fracture network by utilizing the observed field data to define the orientation, size, intensity, and spatial model [12]. The success of the DFN technology depends on the quality and quantity of the fracture network acquired from the field. Hence, the method relies on the accuracy of the fracture data collection techniques. After a successful collection of quality data from the site visit, the DFNs then make use of the stochastic analyses to give a range of possible models which will indicate the real mapping area of the slope or tunnel with their stable performance. Alghalandis et al. [13] defined the DFN as a stochastic approach that represents only one possibility derived from statistical distributions of dip directions, dip angles, intensities, and persistence of each fracture set.

Miyoshi et al. [10] stated that the DFN makes use of the statistical distribution principle to describe the fracture parameters such as the fracture location, orientation, intensity, and size. The acquired data from mapping and site investigation are used to create a 3D stochastic model presenting the statistics that describe properties of the specific discontinuities such as faults and persistence of fracture in the rock mass. The basic fracture properties that are required to generate a DFN model are classified into primary and secondary properties. According to Elmo et al., [14], the primary properties entail the geometry of the fracture network while the secondary properties of the specific applications of the DFN model were discussed in Elmo [15]. Rogers and Booth [16] modified the primary and secondary properties of the DFN by adding the sources of the data tabulated in Table 1.

However, to obtain a great amount of persistence during mapping, a Bayesian bootstrap method can be applied to generate rational results [17]. The bootstrap technique is a statistical approach that focuses on the random sampling from an original sample used to create a pseudo-replicate sample of fracture orientation [10], that is, the method provides a sum of the DFN model to simulate highly dispersed orientation data. Similarly, Dijkstra's shortest-path algorithm can also be used to evaluate the linear discontinuity persistence based on the 3D DFN [17], that is, the extent to which the size of the discontinuities persists in rock masses. Although the shortest-path algorithm approach is relatively difficult to use due to the complexity of 3D spatial analysis, it is considerably easier to estimate the persistence of joints and trace the length of discontinuities in 2D. Generally, the stochastic DFN model approach also has its limitations. Mathis [18] stated the limitations of using the stochastic approach include the uncertainties in statistical parameters and oversimplifications of fracture geometries and topologies. Likewise, the DFN model often led to complex geometric configurations, that is, the modelling of DFN involves thousands of fractures [19]. Recent studies by [20–22] showed that the establishment of a hybrid DFN approach can be accounted for by the advantages of both stochastic and geological approaches to create a better 3D fracture network that can present a realistic geological system. Moreover, Hyman [23] stated that the main challenge of using the DFN approach to simulate fluid flow is the creation of an efficient and scalable workflow.

Table 1. List of required primary and secondary properties for DFN modelling and the sources of these properties (modified after Rogers and Booth, 2014 [16]).

S/N	Primary Properties	Sources of Data
1	Fracture intensity distribution	Core sample orientation, borehole image interpretation, and mapping
2	Orientation distribution	Core sample orientation, borehole image log, and mapping
3	Fracture size distribution	Mapping, ideally at multiple scales
4	Spatial variation	Interpretation of borehole or mapping data
	Secondary Properties	
5	Fracture stiffness properties	Shear testing techniques from literatures
6	Fracture shear properties	Core logging, mapping, and shear testing
7	Aperture distribution	Core logging, mapping, and hydraulic testing
8	Storativity distribution	Packer testing, well testing
9	Termination percentage	Mapping
10	Fracture transmissivity distribution	Packer testing

The framework for DFN was discussed by Davy [4]. In their study, a five (5) step framework, whose core components are a set of deterministic data and statistical properties, is shown in Figure 1.

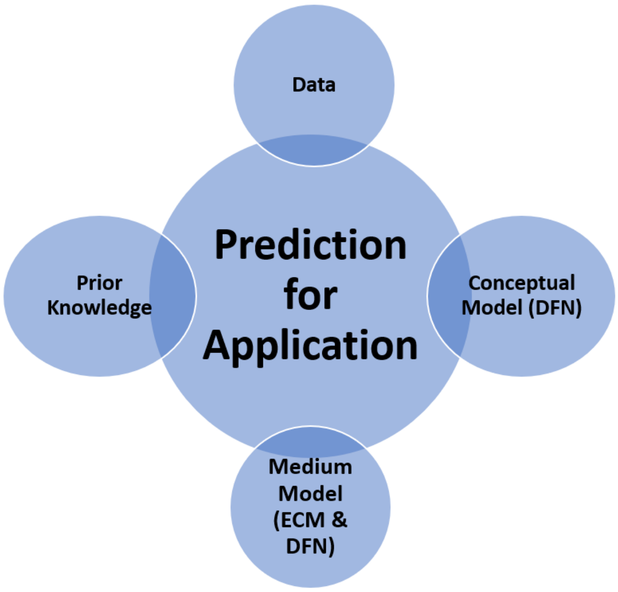


Figure 1. The five (5) basic steps to DFN framework (adapted from Davy [4]).

These properties include the black circle arrow which is developed from the blue arrow and the prior knowledge which is the yellow arrow. The outcome of the model can either be empirical or theoretical relationships, that is, the DFNs are used to establish a stochastic model which is denoted by the green arrow, and the prediction which is the brown arrow continuum model can either be a discrete DFN model or an equivalent continuum model (ECM). However, Weir and Fowler [12] argued that it is imperative to develop a network model statistical and spatial measurement that describes the actual rock mass. This developed DFN model must represent the actual ground condition. Notably, the DFN model must contain a structural domain that accurately describes the fracture characteristic such as the joint orientation, degree of fracturing, and joint spacing. A workflow on how to create a DFN modelling process and the path to establish an accurate engineering model is presented in Figure 2.

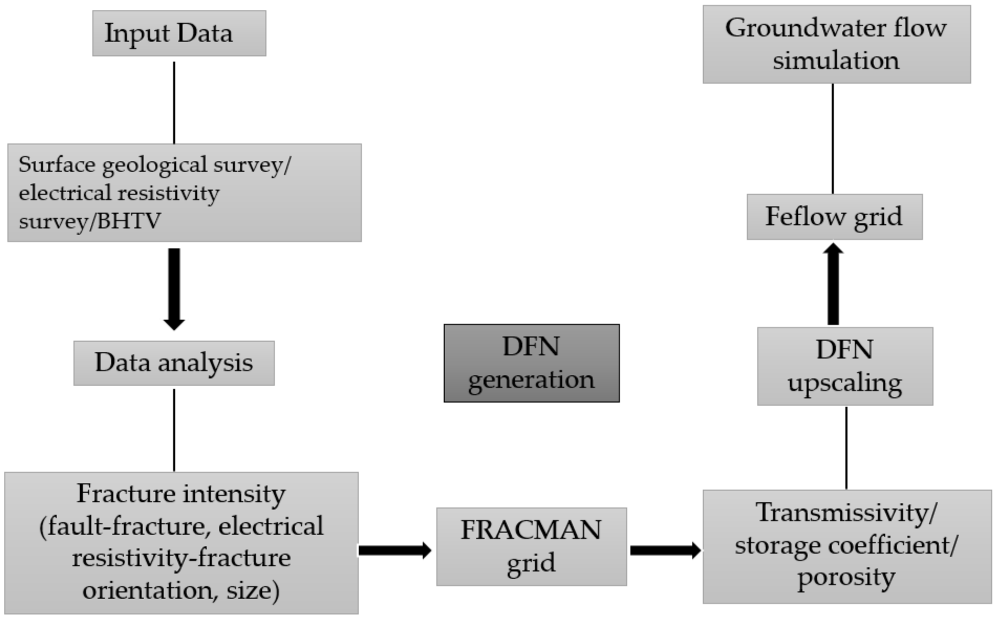


Figure 2. Description of how to build hydraulic properties of fracture rocks using DFN generation and upscaling (adapted from Cheong [24]).

2.2. Principles of Modelling in DFN

Modelling in DFN entails statistically created networks that represent the major structure of the rock mass. The statistically developed DFN model can be created based on the acquired data during the site investigation. These data can be borehole and mapping of the structural domain of the rock mass. According to Dershowitz [25], the modelling of DFN is performed in different forms and shapes, and these include the flat polygon shapes that are the most flexible, realistic, and trending shape representation. Although, modelling of DFNs in a polygonal shape can be complex and requires some specialized stochastic tools. For instance, Alghalandis [26] made use of an enhanced brute-force search and RANSAC approach to generate a DFN from micro seismic data to an enhanced geothermal system. Similarly, Alghalandis's [13] study used Alghalandis discrete fracture network engineering (ADFNE) to proffer solutions to the complexity in geometry and spatial characteristics of rock masses.

Moreover, the choice of selecting input parameters for the DFN modelling also depends on the complexity of the geological structure of the site, the scale, and the purpose of modelling [12,27]. In most cases, modelling of a DFN requires the structural mapping data recorded during site investigation. The acquired data are grouped into four main input parameters, namely fracture orientation, intensity, spatial location, and fracture size [12,28]. The current technological advancement brought about the introduction of digital photogrammetry for mining operations and geotechnical mapping of outcrops. This technology can provide joint properties of the rock surface and other data sets required for the DFN modelling, including large-scale waviness, defect orientation, persistence, joint spacing, block size, and geological structure. Unfortunately, the technology cannot provide the key characteristic of the geological discontinuities, including the joint roughness properties, joint wall strength, and properties of joint infill material [16]. These parameters serve as guidelines to generate a 3D stochastic model representation of the site.

2.2.1. Fracture Orientation

Fracture orientations in rock mass are mostly determined by the stress field conditions of the rock and other factors such as the geochemical properties and local and regional scales [26]. Unfortunately, it is impossible to have a 3D representation of the fracture or map the fracture present in the subsurface. The common way of generating information related to fracture distribution (orientations, intensities, apertures, and lengths) in the subsurface can be achieved by taking measurements from the outcrop or carrying out well-loggings. From this, a stochastic fracture network describes a single fracture property in both 3D and 2D, such as fracture shape (in 3D), length (in 2D), orientation, aperture, and position of the fracture centre [29].

Tuckwell [30] emphasized that fractures with different orientations possibly belong to different fracture sets because of different stress conditions. Mostly, in each fracture set, the orientation is highly concentrated with a high value of the degree of concentration of the distribution around the mean direction [31]. Hence, the fracture orientation is the only important factor to differentiate various fracture sets and the neighbouring and overprinting criteria between fractures on an outcrop map [32]. The fracture orientation describes the attitude of a discontinuity in space, which measures the dip and the dip of the joint. The orientation of the fracture network in the DFN model can be created by the statistical approach of aggregate or disaggregate [28]. The statistical approach can be represented as Fisher, Bingham bivariate Fisher, and bivariate Bingham. Alghalandis [26] argued that the probability distributions approach is the most convenient and widely used technique for summarizing fracture orientations.

Similar to the statistical method, the common probability distribution approach for summarizing fracture orientation includes the von-Mises (the circular normal) for 2D and the Fisher distribution and uniform distribution for 3D. The von-Mises–Fisher distribution is usually used to describe the orientation of the fractures [31,33,34]. According to Staub [35], of all the above-mentioned approaches, the Fisher distribution is the most commonly used. This is because it presents an analogue method of normal distribution for fracture data, and the parameters from the mapping can be easily derived. Likewise, Miyoshi [10] added that in cases where the orientation of the data is dispersed, it would be difficult to define the fracture set. Although, the bootstrap method can be applied to generate an aggregate DFN model. The bootstrap will create a pseudo-replicate sample of fracture orientation. According to Alghalandis [26], the orientation of fractures can be defined as oriented, semi-oriented, and fractures with no orientation. The description of the orientation depends on the generated value of k from the von-Mises distribution. For instance, the von-Mises distributions set k to be equal to 1000 for oriented fractures, k is 10 for semi-oriented, and k is 0 for randomly oriented fractures, as shown in Figure 3.

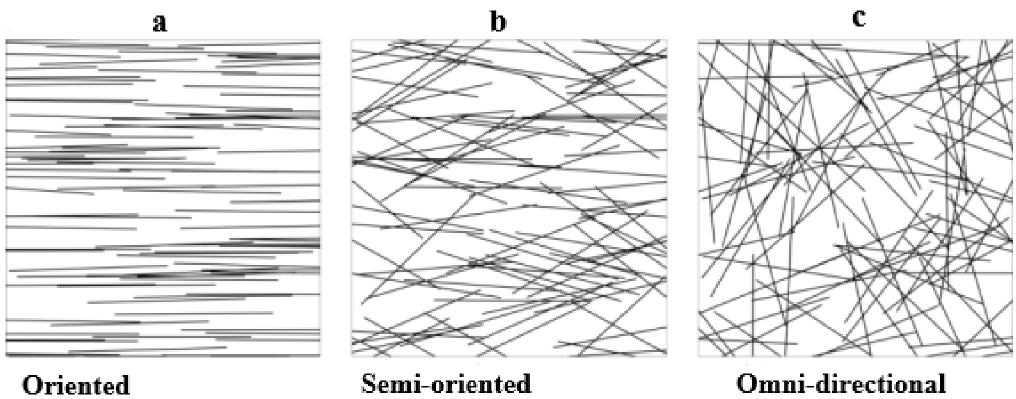


Figure 3. Different fracture orientations: (**a**) fractures oriented in E–W direction (von-Mises distribution = 0 and k = 1000); (**b**) fracture partially oriented towards E–W (von-Mises distribution = 0 and k = 10); (**c**) fractures that are randomly oriented (von-Mises distribution = 0 and k = 0).

2.2.2. Fracture Intensity

Fracture intensity is one of the factors that describes the geometrical properties of the rock mass. Zhang and Einstein [36] defined fracture intensity as the surface area of discontinuities per unit volume. Lu [37] stated that the fracture intensity is the ratio of the total area of discontinuities and the volume of the rock mass considered. The intensity of jointed rock mass plays an important role in determining the mechanical properties and hydraulic conductivity of discontinuous rock mass. Therefore, it is important to accurately determine the fracture intensity in a rock mass to be able to realistically model the 3D representation of the rock mass [12]. Although, a rock mass demonstrates spatial variability in fracture intensity due to the variation in geometric constituent in a rock mass [37]. In estimating the fracture intensity, the fracture distribution size and the number of discontinuities must be known. However, the fracture tensor can be used to quantitatively describe the intensity and the orientation of the fracture. Kachanov [38] quantified the geometry of microcracks in rocks by introducing a tensor α_{ij}, that is, the geometry of cracks in the rock mass can be defined by Equation (1):

$$\alpha_{ij} = \frac{1}{v}\sum_{k=1}^{m(v)}\left[S^{(k)}\right]^{3/2} {n_i}^{(k)}{n_j}^{(k)} \quad (1)$$

where V denotes the volume of the rock mass, $S^{(k)}$ represents the kth discontinuity, and $m^{(V)}$ is the number of discontinuities in volume V, while $n_i(^k)$ and $n_j(^k)$ (i,j = x, y, z) are the components of the unit normal vector of the kth discontinuity with respect to orthogonal reference axes i and j (i, j = x, y, z). Dershowitz [39] used the FracMan discrete fracture code to estimate the intensity of the discontinuities. This is carried out by using the discrete fracture code to generate discontinuity networks with known discontinuity size distribution and intensity to simulate the field sampling process. According to Weismüller [32], the fracture intensity is denoted by p_{ij}. In the p_{ij} system, the subscript i represents the dimension of the sample, while the second index subscript j refers to the dimension of the measurement. Lu [37] explained the use of the two-dimensional fracture intensity (P_{21}) method to predict the fracture intensity in a rock mass. This method makes use of Poisson distribution to model the uncertainty of a P_{21} measurement. The outcome of their study showed that the uncertainty of P_{21} measurement can be exhibited by the size of the sampling window, fracture diameter, and fracture intensity. Weir and Fowler [12] argued that the first step in characterizing fracture intensity is the identification of zones of rock mass where the degree of fracturing remains constant over intervals significant to the scale of the model (typically 10 s to 100 s of meters).

2.2.3. Spatial Distribution

The spatial distribution of fractures is determined from the spacing measurements along the sampling lines such as a borehole or the 2D rock face mapping. Zhu [29] stated that it is a complex procedure to characterize the position of the fracture centre. In the studies of Berkowitz and Adler [40], Bour and Davy [41], and Berkowitz [42], they emphasized the importance of fracture centre. That is, when fractures are uniformly distributed from the centre, the fracture orientation and number of fractures per unit volume can be determined. Although, the spatial density distribution brings the clustering effects and might be closer to reality [43]. Over the years, one of the significant changes that has taken place in DFN technology is the evolution from a simple geometric model where the spatial distribution of fracturing is constant within a volume.

However, the commonly used approach to record the spatial distribution of fracture networks is the one-dimensional sampling technique. This approach measures the spacing between fractures in a given fracture set through the map of fracture traces exposed on the rock mass. In Table 1, Rogers and Booth [16] stated that the source of data for spatial variation for DFN modelling can be taken from the analysis of borehole or mapping data. The data were obtained from drilling through the subsurface, which provides quality data detailing the geotechnical logging, core photographs, and rigorous quality-control program. The core samples from the drilling will highlight parameters of the fracture orientation, intensity, and spatial model for the drilling surface. An example of the spatial model from drilling is presented in Table 2 by [12]. The table summarizes the spatial input data and resultant value for the DFN modelling.

Table 2. Sample of spatial data for DFN in shale unit [12].

Domain	Data Sources	Spatial Model	Mean P_{10}	Sizes (m)		Total Number of Models
				Min	Max	
1	11 boreholes	Enhanced Baecher	0.007	25	400	35
2	7 boreholes		0.018	75	400	24
4	Recent underground decline and 4 boreholes		0.014	25	400	26

From the drilling, the stereographic orientation was recorded where the fracture orientation and Fisher dispersion were obtained for each of the data sets. Thereafter, an enhanced Baecher spatial distribution from the Poisson process model was applied for each model. The enhanced Baecher model works on the principle of using a fracture centre located uniformly in space and applying the Poisson process to create a disk with a given radius and orientation. According to Yue [44], the enhanced Baecher model makes use of fracture shape to generate a polygon with three to sixteen sides. The established polygon can be equilateral or elongated with the ratio of major to minor axis size and orientation being defined.

2.2.4. Fracture Size and Length

The fracture size in the DFN model is regarded as the most challenging parameter in the DFN to quantify, particularly from borehole parameters [12]. Most studies depend on literature to determine the size and the length of fractures of the same type of rock at different locations. Alternatively, the size and the length are estimated from a back-analysis approach, that is, the size and the length are estimated using an empirical relationship between the fracture length and aperture of the rock sample [45]. However, before the empirical method can be used, the rock mass must have the same or similar properties to the rock at hand.

Several researchers have discussed several methods of determining the fracture size using different models. Li [46] described the fracture size in six forms; these include orthogonal model, Baecher disk model, Veneziano model, Dershowitz model, Mosaic block tessellation and modified tessellation models, and lastly, the finite element method (FEM). In the orthogonal model, the model assumes three mutually orthogonal sets of parallel fractures. The fracture size can be determined as the space in between the fracture plane of a rectangular shape fracture. The Baecher disk model assumes that the fracture shape has a circular structure, and the fracture size can be determined by the diameter of the fracture. In the Veneziano model, the fracture is polygonal, and the fracture size is defined by the intensity of the Poisson line processed and the proportion of polygons marked as fractures. In Dershowitz models, the fracture shape is a polygon, the fracture size is also determined by the intensity of the Poisson plane processes, and the proportion of the polygon is marked as a fracture. Both mosaic block tessellation models and modified tessellation models depend on Poisson–Voronoi tessellation models where the fracture size is determined by the density of Poisson points from the Voronoi polygon. Lastly, the finite element method's (FEM) model approach discretized the fracture into triangular meshes for hydromechanics analysis [47–50].

During DFN modelling, the user must be able to differentiate between the size and the length of fractures from the rock mapping data. It was also mentioned by Elmo [28] that it is critical to differentiate between the fracture length and size as input parameters for the DFN modelling. Miyoshi [10] defined the fracture size as an equivalent radius if the fracture under investigation is assumed to be polygonal, that is, the fracture size measured from the field is traced with the polygon fracture with a free surface equivalent to the measuring plane in the field. The fracture size or length is usually obtained from bench or outcrop trace mapping. It is necessary to convert the fracture length to an equivalent radius distribution to be incorporated into the DFN model [12]. The length of the fracture in the DFN model for characterizing fluid flow in fractured rock masses plays a key role in generating fracture model networks. An increase in fracture length causes an increase in the permeability of the fracture network. In a study by Zhang [51], the fracture length was increased from 3 m to 13 m, causing an exponential increment in the value of permeability by approximately two orders of magnitude. Likewise, an increment in fracture length also caused an increment in the intersection length and number of intersections. The result of the study by Zhang [51] showed that the fracture length influenced the permeability of the fracture more than that of the geometric parameters, including the intersection length and the number of intersections. Similarly, Liu [52] acknowledged that longer fractures usually have higher permeabilities and larger apertures than shorter fractures. Schnabel's [53] study made use of the RANSAC shape detection tool to obtain the fracture size from the point cloud data using the cloud compare software. The dip and dip angle are automatically generated using the plane-patch filter RiSCAN Pro software. Li [46] emphasized the importance of the shape and sizes of polygonal fractures. The study stated that a better way of estimating the size is to focus on the vertices of the polygon.

3. Data Capturing for DFN Modelling

Data capturing in a DFN is the most critical process that influences the outcome of the DFN modelling. The quality of the input data determines the outcome of the fracture network. At the end of the modelling, the 3D representation of the discontinuous surface would depend on the quality of field data acquired during site investigations. According to Weir and Fowler [12], it is difficult to conceptually describe the geological interpretation of a rock mass, that is, the relationship between various fracture sets and their properties. It is important to interpret the fracture distribution and properties in terms of their characteristics such as the joint roughness, joint infill materials, and termination of joints. Therefore, to develop a robust DFN model that represents the ideal geometry of fractures, there is a need to generate large statistically and spatially located data that can be georeferenced. For instance, the construction of a tunnel in a highly fractured rock mass requires details of a subsurface fracture network to evaluate the mechanical response. However, reliable mapping data can be used to characterize and establish a sound 3D representation of the fracture geometry.

Over the years, there have been various methods of recording characteristics of fracture networks from a surface. The approaches to map rock surface have been evolving using traditional and modern technologies to capture fracture properties of the rock mass. Modern technologies present digitalized fracture geometry with the advantage of capturing a huge amount of data within a short period of time. Modelling with a DFN heavily depends on the quality of the input parameters from the structural properties of the rock mass [8]. The traditional approach of measuring the spatial data such as the dip and strike is generally performed by hand with a compass or inclinometer, which is dangerous when collecting data in an unstable area. Moreover, the approach is time-consuming. Zhang and Einstein [54] stated that the traditional approach for acquiring input parameters for the DFNs is derived from the manual method of mapping rock faces such as the use of the scanline sampling method, circle sampling, area or window sampling, and use of the geological compass. Although, the manual approach was reported to be time-consuming and thus not often used in mining operations [8]. Similarly, Weir and Fowler [12] stated that the challenge of using the traditional method of kinematic analyses is that assumption is made about the infinite joint length intersecting the excavation plane. Ovaskainen [55] argued that the source of uncertainties in using a manual approach can be attributed to the availability and size of the outcrops and variable visibility of fractures on the outcrop surface caused by censoring, such as the limitation in sample sizes and sample area, which mask the true length of fractures. The data obtained from the mapping will provide information on the strength of the rock mass and its deformability properties, the geological structure, rock mass structure, and the properties of major planes of weakness [56]. Consequently, the absence of quality and comprehensive data from the field can impact the stability analysis of excavation in rock, that is, the better the information available from the mapping field, the better the outcome of the engineering analysis.

The advancement of technology has brought about accuracy and precision in field data capturing. Apart from the accuracy and precision, the introduction of digital mapping instruments such as the terrestrial laser scanner, borehole televiewers, and photogrammetry can generate high-density 3D point cloud data from rock surface mapping [57]. According to Cawood [58], the laser scanning system provides a complete and detailed mapping of a rock mass in mining. Several researchers [59–63] have discussed the strengths and flaws of using the laser scanner instrument and photogrammetry approach in rock surface mapping.

3.1. DFN Data Acquisition with 3D Laser Scanning Technologies

The 3D laser scanning technology is an instrument used for mapping, surveying, and monitoring rock mass movement in mining. The instrument is a non-contact technology that captures high-density data by utilizing a transmitted and reflected laser beam to determine the distance of the reflected objects. This principle of measurement and recording data is known as light detection and ranging (LiDAR). The outcome of the scanning generates millions of point cloud data that shows the scan surface and discontinuity data such as joint orientation, fracture density, and length. Kolapo [64] mentioned that laser scanner technologies can digitize a rock face in 3D with a fast scanning speed and high resolution of up to millimetre accuracy. The 3D laser scanning technologies have greatly improved the methods of collecting in situ data due to the convenient mode of operation. The instrument provides a uniform data format and mapping algorithm that makes it possible to extract accurate and precise data regarding the discontinuities [65]. The accuracy and speed of data acquisition over wide areas enable the creation of 3D models of geological bodies.

Moreover, after scanning tasks, the result is 3D point cloud data. The point cloud data provide a 3D representation of the scan surface made up of single points that are densely populated. The raw point cloud needs to be processed to eliminate human mapping errors or blunders that may be present. The efficiency and accuracy of the acquired point depend on the skill and experience of the operator. The knowledge of the source of errors in using laser scanning technologies is essential in generating reliable point cloud data. The acquired point cloud data can be transferred into computer software packages for processing and further analysis; although, the time taken for processing the data is more than the time required to manually collect the data [66].

The processing software will improve the display performance such as the feature extraction and fusion with imagery data [64]. Tracing of fractures in the mapping of a rock surface using point cloud data was carried out. For instance, Maerz [67] performed the extraction of the geometric parameters of a discontinuous rock mass from laser scans. Several researchers have introduced various computer software packages to extract the geological features from laser scanner point cloud data. Riquelme [68] applied the discontinuity set extractor (DSE) method to estimate the discontinuity spacing in the rock mass. Deweza [69] used the FACETs function on cloud compare software to perform planar extraction and to calculate the azimuth (dip and dip direction) of fractures. Recently, there have been developments in various intelligence algorithms that can identify discontinuity in laser scans. These include the random sample consensus (RANSAC) discussed in Ferrero [70] and the principal component analysis (PCA) approach by Gomes [71]. Likewise, Guo [72] used 1D truncated Fourier series and a curvature-weighted Laplacian-like smoothing method to trace and identify discontinuity directly from 3D point cloud data; Gigli and Casagli [73] applied a MATLAB tool called discontinuity analysis (DiAna) to analyze the rock mass discontinuities from laser scanning point cloud data; Ge [66] proposed a modified region growing (MRG) algorithm to identify discontinuities from the point cloud data. Similarly, Zhang [65] discussed the five (5) steps presented in Figure 4 used to trace the intersection line of two adjacent discontinuity planes.

Figure 4. Steps taken to trace discontinuity from point cloud data (Adapted from [65]).

In Vazaios's [74] study, polygonal models were used to assess the structural feature of a rock mass such as joint orientation and fracture length. In this approach, the orientation of fractures present is determined by fitting planes to the selected areas of the polygon models after visual inspection. Thereafter, the direction cosines of the normal of these best-fit planes are used to evaluate the dip and the direction of fractures as shown in Figure 5a,b.

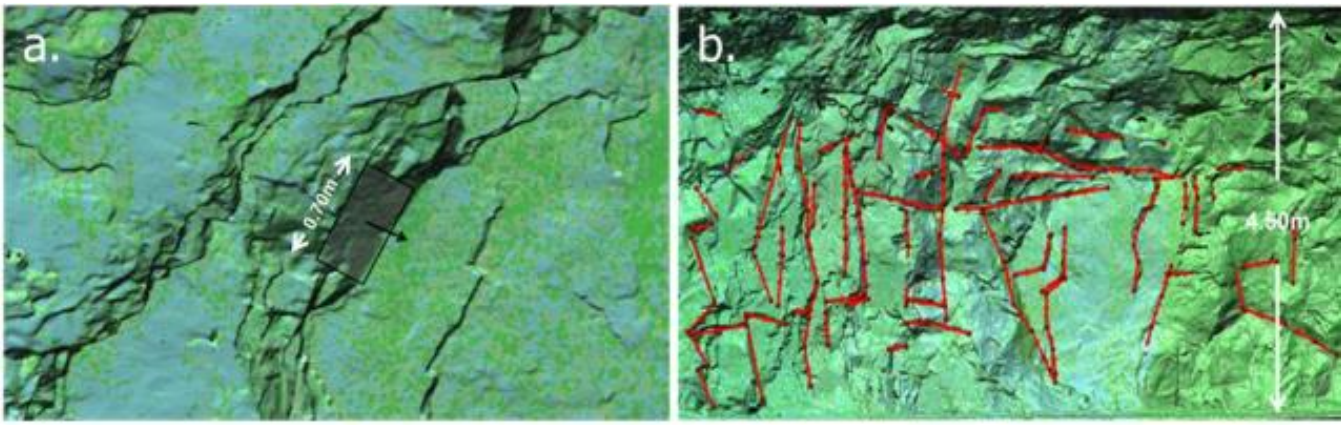


Figure 5. (**a**) Virtual mapping of discontinuities; (**b**) tracing fracture on 3D surface of a rock mass (adapted from [74]).

3.2. Photogrammetry Approach of Collecting DFN Data

Like 3D laser scanning instruments, the photogrammetry approach also produces digital elevation models (DEM) at high densities. The method makes use of digital photography of a surface captured from two or different locations to determine the depth and the dimension of space [16]. The mode of operation is by overlapping multiple photographs to generate DEM that can create 3D models of the surface. This approach makes use of motion video of surfaces or objects with cameras to generate 3D space to estimate X, Y, and Z coordinates for each pixel of an image capture. The photogrammetric approach provides a combination of 3D and spectral remote sensing data in a flexibly and cost-effective manner [75]. The method has been described as the main tool to compute the volume of ore in an open pit mine [76].

In the early 20th century, photogrammetry principles were introduced with the use of stereoscopic instruments for the construction of topographic maps. The advancement in technologies has brought about the integration of spectral remote-sensing data to generate DEM. The emergence of modern and high-resolution digital cameras proffers solutions to the restriction of the number of photographs that can be taken during data collection and provides quality pictures that can easily be assessed during data collection. Bemis [77] discussed that the noticeable barrier in using this approach is achieving the optimal positioning for the camera relative to the object of interest due to topography, vegetation, etc. Although, the barrier is being reduced over the years with the advent of high flight height digital photography from UAVs that provides improved synoptic views from overhead. Rogers and Booth [16] stated that a noticeable limitation in the use of digital photogrammetry for geotechnical mapping is that it cannot record measurements of certain key characteristics such as the thickness and type of infill materials, joint wall strength properties, and small-scale roughness. This is the reason why the remotely taken measurement by photogrammetry mapping is commonly supplemented with conventional outcrop mapping data.

The photogrammetry technique has been widely used in mapping, monitoring, and evaluating the stability of rock mass in mining operations. Traditionally, it is difficult to survey and collect geological data from high walls in open pit mines. The geotechnical engineers and geologists must walk up to the high walls to physically capture data needed for high walls stability analysis and to plan for the optimal mineral extraction. The modern photogrammetry approach can provide engineers with a user-friendly tool for rapid data acquisition. It provides a remote geotechnical mapping of rock slopes without physical access to the rock mass. The photogrammetry method of data acquisition works perfectly with DFN modelling as it can provide large and spatially located geotechnical data sets required to produce the 3D representation of the surface. The technique permits the use a probabilistic method for evaluating kinematic stability and rock block size distributions [16]. Application of photogrammetry approach in open pit mine was presented by Patikova [78] where high-resolution aerial images with low flight altitude are taken for open pit mining purposes. High-speed computers equipped with photogrammetric software are used to generate the digital terrain modelling (DTM) of the mine for volume calculation, as shown in Figure 6a,b.

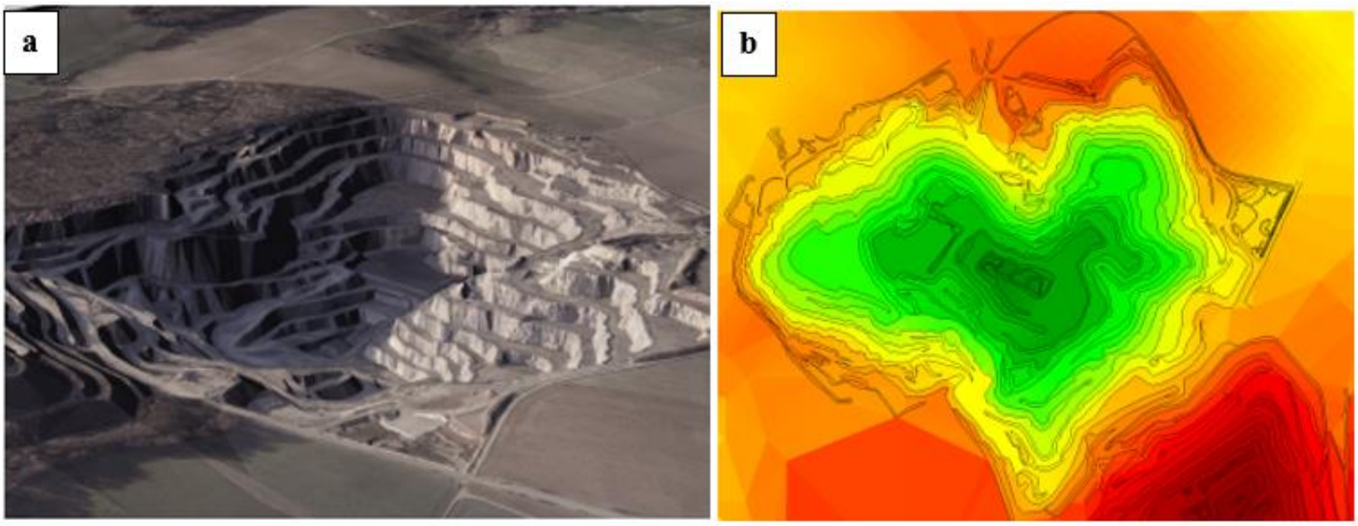


Figure 6. (**a**) Three-dimensional view of the open pit; (**b**) DTM representation of the open pit (adapted from [78]).

Moreover, Rogers [79] explained the application of the photogrammetric method to acquire fracture orientation for DFN modelling. The study stated the importance of photogrammetry in generating large, spatial geotechnical data sets required to produce a robust 3D modelling of the surface.

This approach produces large volumes of data, which makes it possible to develop DFN models for the actual fracture observation from the field for various geotechnical and geomechanical evaluations. This is one of the advantages of the photogrammetric approach in the DFN modelling process. The generation of the high density of data makes it possible for defining the effects of fracture properties on both the global and local DFN properties. Availability of technologies integrated with multiple sensors allows acquisition of fractures from mapping and photogrammetry approaches to produce exact fracture distribution of the mapped surface. The workflow for DFN model development from conditioned to actual mapping data is presented in Figure 7.

Likewise, the method has the potential to develop DFN models directly from photogrammetric surveys for evaluation of kinematic analysis from a structural description that accurately reflects the scanned location, providing a significant step forward in modelling capability. According to Rogers [79], the result of the analysis has the ability to make a sound decision on underground excavation techniques and ground support designs as a result of the heterogeneity of the rock mass. However, several studies have also used the photogrammetric approach for DFN modelling in the underground mining environment. For instance, Grenon [8] used photogrammetry tools to provide input parameters for generating a series of DFN models at the Éléonore underground mine in Canada. Three images were taken from three rock faces (Amn-0354, Gmn-0354-1s, and Gmn-0357-1n) at the development stage. These images were used to construct the 3D numerical modelling of the rock mass with orientations of 88°/252°, 87°/185°, and 86°/161° for the Amn-0354, Gmn-0354-1s, and Gmn-0357-1n drifts, respectively. The availability of the data facilitates the calibration of the DFN models at the mine. Similarly, Rogers and Booth [16] used the photogrammetric method to provide input parameters required for the DFN of rock mass in a tunnel. The study explained that the instrument can generate 3D fracture models driven by the statistical structural data and conditioned to the features observed by the photogrammetry to yield a synthetic rock mass on which improved design methods can be applied. The application of the photogrammetric approach for DFN modelling in underground mines was recorded by Benton [80]. Photogrammetric surveys were carried out in the 54 ramps at the depth of 2.1 kilometres at the Lucky Friday mine to produce measurements to aid in the interpretation of measurements from conventional instruments.

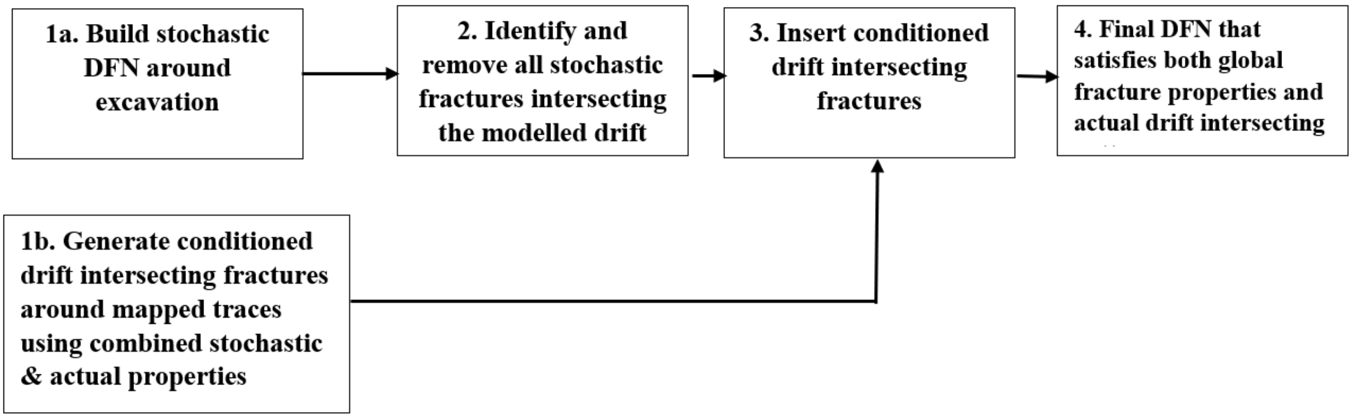


Figure 7. Interface for the development of DFN model from conditioned to actual mapping data (adapted from [79]).

4. Application of DFN Approach in Predicting Stability Analysis of Jointed Rock

DFN has been widely applied to study the stability of important engineering structures and utilities in jointed rocks at the surface, underground, small-scale, and large-scale. The areas of deployment of this tool include the stability of the fractured rock slope, coal seam longwall face stability, highway rock slope stability, high-level radioactive waste disposal wells, spent fuel reprocessing, hydrocarbon reservoirs, hydropower projects, and tunneling [1,81–87]. Table 3 provides a summary of DFN models developed for different engineering applications and structures. For each summarized area of application, the characteristics of the rock mass, model properties, figures, and drawbacks of the model were briefly discussed. Further explanation of the applications of the DFN model in these areas is provided in Section 5.

Table 3. Summary of developed DFN models in various engineering applications.

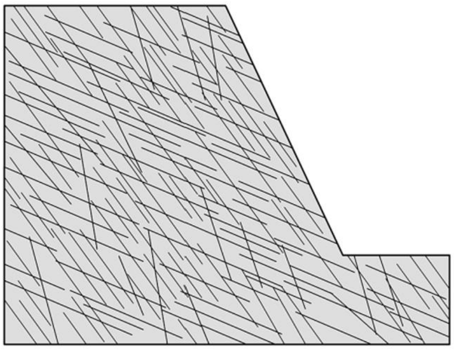
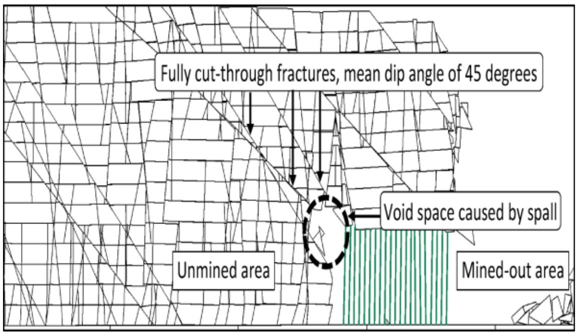
Reference	Summary of Developed DFN Models
Adapted from Li [81]	Geological/geotechnical characteristics: bedrock sliding body fracture and rock matrix fracture.  Figure: Numerical fractured rock slope model with regularly distributed fractures. Model properties: geometry of length, height, and slope angle as 96 m and 125 m, 50 m, and 95 m and 30° and 40°, for single and multi-fractures containing slopes, respectively. Sliding volume as 447.84 m^3 per unit width and the interface or fracture length as 69.282 m for a slope containing one single fracture. Field of deployment: stability of the fractured rock slope. Remarks: The developed DFN model is constrained by the employment of simplified and assumed material parameters and constitutive relations which may affect the accuracy of the model. The unavailability of groundwater flow within the slope may also limit the accuracy of the model.
Adapted from Le and Oh. [82]	Geological/geotechnical characteristics: Average sedimentary thickness of 540 m which mainly consists of sandstone, siltstone, gritstone, and coal seams. Two main mine-scale fault sets whose strikes are in parallel and meridian directions. The parallel-oriented strike faults plunge to the north or north–northwest, and their dip angle ranges from 55 to 75 degrees. The mine contains many small-scale faults whose strike directions are like those of the main faults. The panel has an average cover depth of 200 m, extraction thickness of 7.98 m, and seam dip angle of less than 10 degrees. The immediate roof of the coal seam is mainly siltstone with an average thickness of 8.48 m. The main roof is mainly sandstone with a thickness of 16.72 m.  Figure: The impact of a 45-degree fracture dip angle on the stability of the longwall face. Model properties: The model used plane-strain condition because the face advance in panel length was much greater than that in panel width. The model dimensions in vertical direction were 113 m, 250 m in strike direction, and 1 m in the out-of-plane direction. DFN domain of length 50 m and thickness of 8 m. The siltstone floor coal seam, siltstone immediate roof, sandstone main roof, and siltstone overburden measured 40, 8, 8.5, 16.5, and 40 metres in thickness, respectively, from bottom to top. Bedding planes spacing of 0.5 m, mean dip angle of 115, and 90 degrees for the first and second fracture sets, respectively. Field of deployment: coal seam longwall face stability. Remarks: Due to limited field mapping and laboratory testing, a few assumptions were made to determine the inputs for the model; nevertheless, their impact on the model's outputs is minimized by a comprehensive calibration and validation procedure versus field measurement.

Table 3. *Cont.*

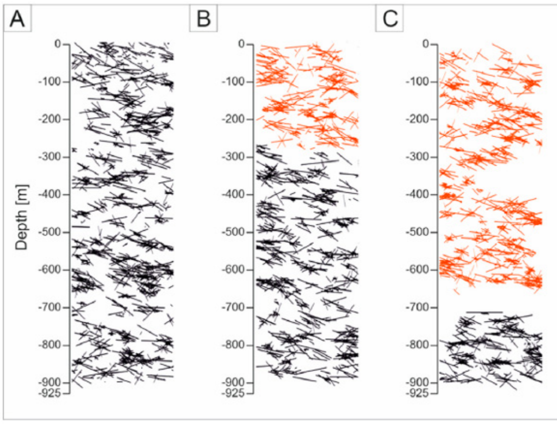
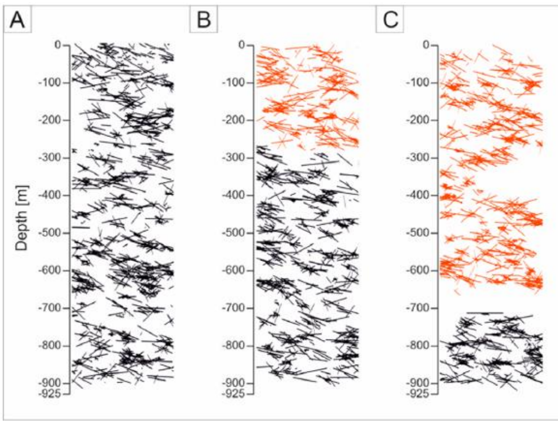
Reference	Summary of Developed DFN Models
Adapted from Singh [83]	Geological/geotechnical characteristics: Upper Tal Formation dominantly consisting of orthoquartzite and arkosic sandstone and partial partings of mudstone. Cretaceous anikot shelly limestone. The rock group belongs to a regional-scale syncline known as Garhwal Syncline.  Figure: Developed DFN for site 2 having three joint sets coloured yellow, pink, and dark green (not to scale). Model properties: Three persistent joint sets were considered per each of the studied sites in the DFN model. The length of the joints range between 0.9 m ± 1.23 and 4.75 m ± 0.87 for the three sites. Both log-normal and power-law were the length distributions adopted. The average Fisher dip/dip direction ranged between 35/30 and 80/80, and the average fracture intensities (P_{32}) were between 0.451 and 4.5. Field of deployment: rock slope stability along national highway. Remarks: Due to the broad variability of rock mass properties, engineering professionals are encouraged to study each rock mass independently in the proximity of structurally damaged zones.
Tóth [84]	Geological/geotechnical characteristics: The host rock is the Boda Claystone Formation (BCF). The formation consists of well-compacted reddish-brown claystone, siltstone, and albitolite (authigenic albite >50%) with dolomite and sandstone intercalations. The formation maximum thickness is 1000 m and with a distribution area of 150 square kilometres. The average dip direction of the bedding in the well is SE–SSE, and the dip is 40° based on acoustic borehole televiewer (BHTV) observations. Four classes of veins including branched veins, straight veins, *en echelon* vein arrays, and breccia-like veins characterized the deepest well of the formation (BAF-2). In the BAF–2 well, the average dip values of the vein types are 42° (branched veins), 70° (straight veins), and 22° (*en echelon* vein arrays).  Figure: Vertical sections of simulated fracture network geometry patterns (**A**–**C**) of the BAF–2 well based on 20 independent runs. Model properties: the DFN model domain was 150 × 150 × 925 m. Field of deployment: High-level radioactive waste repository deep well. The average fracture density (P10) was 9–10 m^{-1}. The average fractal dimension (D) was 1.37 ± 0.05 while the single length exponent (E) value was −0.90 and the F parameter value was 10.00. The borehole planes dip in SSE direction with an average orientation of 162° N—60° E. Remarks: the study is basic and could be improved upon to provide detailed hydrodynamic modelling of the well and its environment.

Table 3. *Cont.*

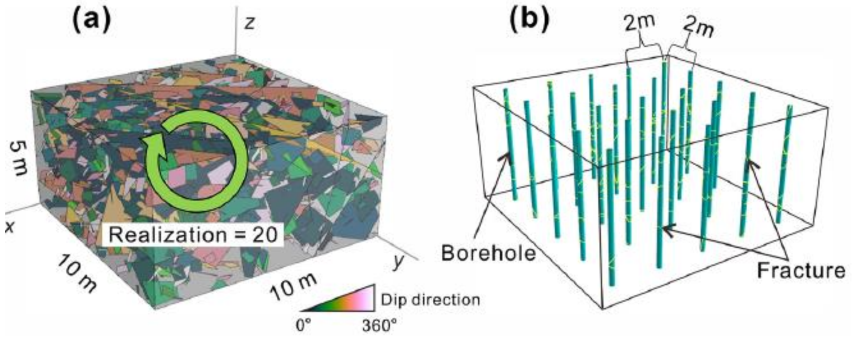
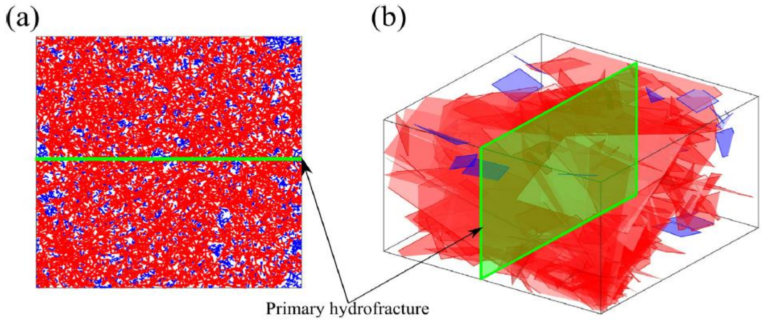
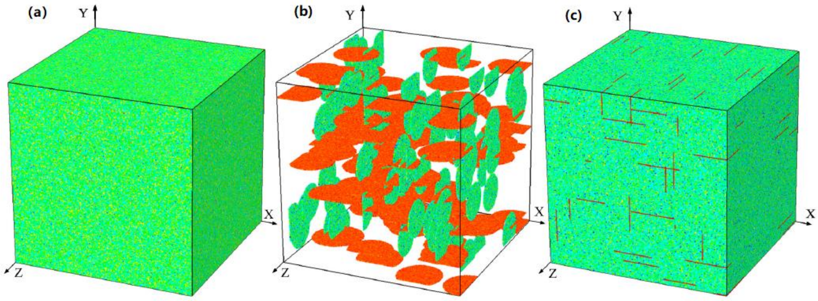
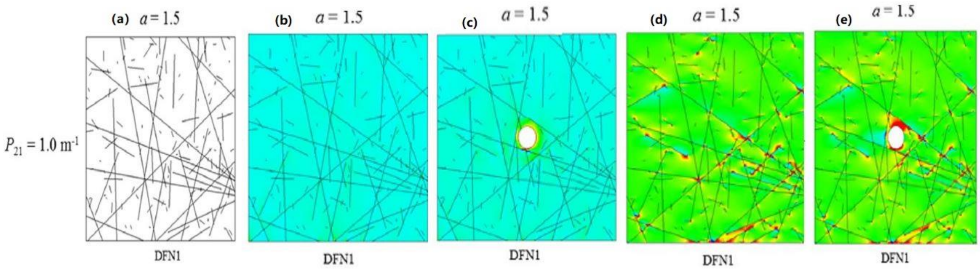
Reference	**Summary of Developed DFN Models**
Adapted from Gao [85]	Geological/geotechnical characteristics: The lithology of the formation is made up of biotite granodiorite in the basement and gravel sand and breccia in the upper layers. Gravel sand and breccia are mixed, and their thickness typically ranges between 0 and 16.8 m from northeast to southwest. The formation is characterized by several structural and weathering fractures that are relatively straight, and the apertures are generally ~0.1–2 mm.  Figure: (**a**) A finite volume DFN model; (**b**) P10 obtained by virtual drilling at an interval of 2 m. Model properties: The rock mass is characterized by at least three fracture sets striking orthogonally towards northeast and northwest directions. The DFN model domain was a cuboid model (length = width = 10 m, height = 5 m). The P32 values range between 0.1 (m^2/m^3) and 4 (m^2/m^3). The fracture size was d_{min} = 2 m, d_{max} = 25 m, b = 1.9343. Field of deployment: spent fuel reprocessing (SFR) site fracture characterization. Remarks: By effectively capturing the variability in fracture spatial intensity, the framework employed in this study addresses the primary drawback of the conventional DFN models. The DFN model can, however, be improved upon and optimized inside this framework in the future by including more important information.
Adapted from Zhu [86]	Geological/geotechnical characteristics: Shale reservoirs with natural fractures and hydro-fractures.  Figure: DFN model: (**a**) 2D fracture network; (**b**) 3D fracture network. Model properties: Stochastic DFN domain with 2D and 3D fractures represented by a line segment (100 m × 100 m) and square plate (50 m × 50 m × 50 m), respectively. The minimum and maximum fracture length used in the power-law distribution is 1 m and 100,000 m. The fractal dimension (*FD*) varies between 1.1 and 2.0 and between 2.1 and 3.0 for 2D and 3D fracture networks, respectively. Fracture intensity (FI) for 2D and 3D fracture networks range between 0.8 and 2.6. Injected fluid pressure of hydraulic fracturing (P_f) = 1; maximum horizontal stress (Sh_{max}) = 1.3 P_f; minimum horizontal stress (Sh_{min}) = 0.8 P_f; vertical stress (Sv) = 1.1 P_f; reservoirs pressure (P_p) = 0.5 P_f; segment length (L_{se}) from between 1 m and 0.2 m. Fracture roughness (JRC) and strength (JCS) and fracture orientation (k) vary between 0 and 20, 0.5 P_f and 18.5 P_f, and 0 and 20, respectively. Field of deployment: sensitivity analysis of the impacts of the fracture network on the formation and development of stimulated reservoirs' volume. Remarks: It is crucial to precisely measure the fracture sealing degree, fracture intensity, and fracture orientations of the subsurface fracture networks to accurately estimate SRV or have a good production prediction.

Table 3. *Cont.*

Reference	**Summary of Developed DFN Models**
Adapted fromWu [87]	Geological/geotechnical characteristics: The rock slope rock mass environment is complex and characterized by three major fracture groups with orientations of 25.98/235.15, 28.16/351.34, and 85.80/94.73, respectively. The trace length and spacing of the three fracture groups are 3.42/1.35, 3.12/1.70, and 2.96/0.69, respectively.  Figure: The three-dimensional equivalent DFN model's construction process (**a**) rock model, (**b**) DFN model, and (**c**) equivalent DFN model. Model properties: The DFN domain was 15 m × 15 m ×15 m and the model of fracture rock masses was 8 m × 8 m × 8 m. Model edges of between 2 m and 15 m were established to investigate scale effects and anisotropy of the fractured rock masses. Displacement load of 2$e-5$ times the model edge per step was applied to the model. The heterogeneity, UCS, elastic modulus, friction angle, and Poisson's ratio of the rock and fracture for the numerical model were, 5 108.9, 37.6, 56, and 0.24; and 2, 5.45, 1.88, 30, and 0.39, respectively. A water head (initial head H1 = 0) with an increase (ΔH) of 0.3 mm/step was applied to the surface in the positive direction of the *Z*-axis, and the water head (H2 = 0) in the corresponding negative direction was zero in the model. Field of deployment: hydropower station project. Remarks: Nevertheless, the suggested paradigm has some drawbacks. The dynamics, impacts of stress changes, fracture interactions, significant displacement, and rotation issues of natural fracture systems cannot be fully considered.
Adapted from Lei [1]	Geological/geotechnical characteristics: The rock mass is a crystalline rock with incompressible grains and networks of fractures of varying lengths and intensities. The intact rock is characterized by density (*P*), young modulus (*E*), Poisson's ratio (v), internal friction angle (φi_{nt}), tensile strength (f_t), cohesion (c), mode I energy release rate (G_I), mode II energy release rate (G_{II}), and matrix permeability (K_m) values of 2680 kg.m^{-3}, 60.0 GPa, 0.25, 35.0°, 15.0 MPa, 55.0 MPa, 74.3 J.m^{-2}, 88.4 J.m^{-2}, and 1 × 10−15 m^2, respectively. The fracture is characterized by residual friction angle (φr), laboratory sample length (L_0), joint roughness coefficient (*JRC*), and joint compressive strength (*JCS*) values of 31.0°, 0.2 m, 150.0 MPa, and10.0, respectively.  Figure: Generated DFN (**a**) length exponent (**a**) = 1.5 and fracture intensity (P_{21}) = 1.0 m^{-1}; (**b**) isotropic in situ stress condition before excavation; (**c**) isotropic in situ stress condition after excavation; (**d**) anisotropic in situ stress condition before excavation; (**e**) isotropic in situ stress condition after excavation. Model properties: The DFN domain was 20 m × 20 m. The fracture length bounds were defined as *lmin* = L/100 = 0.2 m and *lmax* = 100L = 2000 m. Length exponent (a) of 1.5, 2.5, and 3.5 and fracture intensity (P_{21}) values of 1.0, 2.0, and 3.0 m^{-1} were adopted. Overburden stress ($S'v$) = 8.0 MPa, $S'_H/S'v$ =1.0 and 2.0, i.e., S'_H = 8.0 and 16.0 MPa, respectively. Average element size (h) = 5.0 cm, diameter of tunnel (d) = 2 m, penalty term (p) = 600 GPa, and damping coefficient (η) = 6.34 × 105 kg/m·s. Field of deployment: tunnel excavation in fractured rock masses. Remarks: The presence and distribution of natural cracks in the subsurface were found to have a substantial impact on the parameters of the excavation damaged zone (EDZ).

5. General Applications of DFNs

The DFNs have been extensively used in geoengineering projects such as mining operations, civil engineering projects, and the petroleum industry. The application of DFN modelling has become the most versatile, powerful, flexible, and useful tool for advanced engineering analysis that requires the evaluation of fracture geometry in jointed rock masses. It becomes valuable in projects where the fracture network controls the behaviour of the system, such as in stability analysis of a jointed rock mass in a mining rock slope, excavation stability in fractured rock, petroleum cracking, and hydrocarbon and groundwater flow. Alghalandis [13] argued that it is important to establish and analyze the rock mass response, interaction, and complexity of the fracture networks. The outcome of the evaluations will assist in making a sound judgement on the design that will guarantee safety and enhance productivity. Over the last decades, a great number of studies have extensively used DFN modelling as a solution in various engineering projects. Some of the general applications of DFN modelling are described in the next subsections.

5.1. Stability Analysis in Mining Operations

DFN models are widely used in both open pit and underground mining environments. The DFN serves as a tool for modelling the fracture geometry of a rock mass that can influence the stability of high walls in underground and bench configuration in open pit mines. Modelling rock mass structures has been a challenge due to the variability of material properties and uncertainty [88]. The observed variability in material properties is significant because it influences performance in engineering applications [89]. Despite the variation in material properties of the ground, the DFN produces a 3D representation of the rock mass that is captured during data collection. DFN technology poses advantages over other conventional tools in the area of key block stability. The tools can evaluate the fracture system, rock wedge formation, and monitor the deviation of excavation when compared with the actual design. The technology can also be used as a risk assessment tool for geotechnical engineers and geologists in underground stability assessment [79].

In an open pit mining operation, the DFN computer tools were used to create the 3D representation of rock mass structure from statistical distribution. The software integrates fracture data input such as the fracture length, height, spacing, orientation, and aperture to generate a discrete fracture network, compartment and fluid migration pathway analysis, and visualization. The software includes FracMan, SiroModel, FracSim, Alghalandis Discrete Fracture Network (ADFNE), PFLOTRAN, DFNFLOW, DFNSIM, FRANEP, SDFN, MOFRAC, and HATCHFRAC. Kuppusamy [88] used FracMan to generate the bench scale DFN model using a geometric network construction approach from an open pit phosphate-bearing ore mine located in Limpopo province in South Africa. Both scanline and window mapping surveys were conducted across various lithological units. The discontinuity type, persistence, material infilling, joint roughness, termination index aperture, rock type, and groundwater condition were recorded from the scanline while the photogrammetry technique generated the digital map structure where the areas were inaccessible or too dangerous to complete physical mapping surveys. The result of the digitally mapped area of the outcrop is presented in Figure 8 from terrestrial laser scanner point cloud data. Style [90] used the DFMN model to provide stress paths that described the instability of a large slope. The outcome of the study showed that the variation in the mass strength between different fracture orientations has a greater influence on the DFN mass strength in low-strain environments. Foster [91] applied the DFN approach to investigate the hydrological significance and its impact around the open pit. Both DFN technology and the conventional approach of limit equilibrium analysis (LEA) were used to design a bench face slope in an open pit mine by [92,93]. In the study, the strength of the approach lies in the ability of the DFN to adequately capture the characteristics of the rock mass. Similarly, Bonilla-Sierra [94] used the combination of DFN technology and the discrete element method (DEM) to examine and predict unstable wedges and high walls in open pit mines. In the DFN models, the areas that are prone to failures are highlighted. Rogers [95] applied the DFN model to evaluate the volume of unstable material that occurred as a result of three different closure options that led to the formation of key blocks, which was the source of instability at the Chuquicamata open pit mine in Chile. Similarly, Kong [96] used the combination of a 3D terrestrial laser scanner and UAV photogrammetry to identify and measure the fracture properties in a rock mass based on the multi-source fusion of point clouds shown in Figure 8.

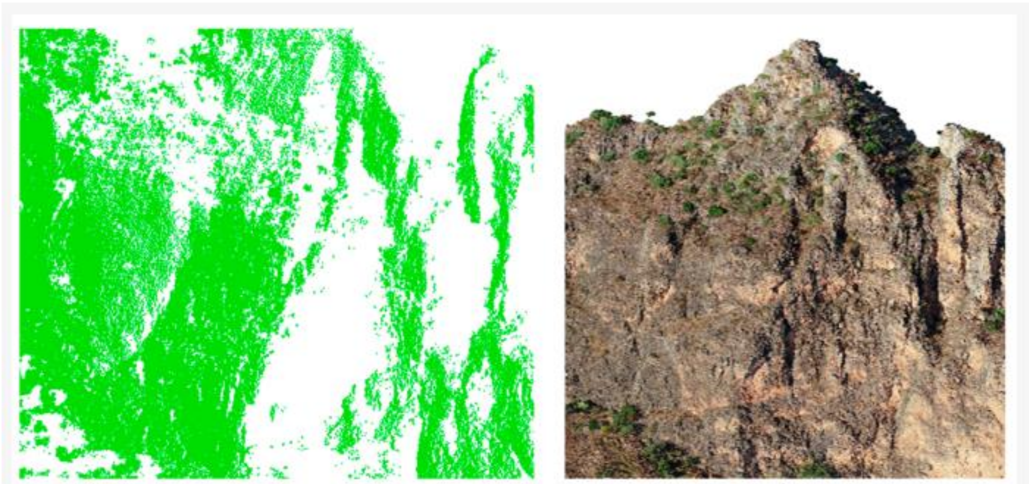


Figure 8. Digitalized outcrop created from TLS point cloud data (adapted from Kong et al., 2022) [96].

Most underground mine applications of DFN models are used in the area of evaluating the stability of underground excavation. DFNs are used to examine the direction and extent of fragmentation in mining operations [97]. More accurate geometric models of in situ fracturing can be developed, and the result of the modelling can serve as an integral tool for advanced geomechanical simulations. The in situ stress conditions of the ground have a greater influence on the stability of an underground excavation. The DFN can be used to describe the in situ fragmentation of the ground conditions. Similarly, Junkin [98] used the DFN approach to derive fracture geometry for a rock engineering system (RES) for an interaction matrix. The study incorporated the fracture geometry from the DFN into the RES framework for blast fragmentation modelling. In massive ore bodies, a hybrid DFN and block caving fragmentation (BCF) was applied to assess fragmentation in block caving projects and mines [99]. Xiao [100] constructed a drift of 40.32 m with a 3D high point cloud data of Jianshan Underground Mine in Panzhihua, Sichuan, China, shown in Figure 9. The result of the point cloud data can be used to make a sound decision on the stability analysis of the mine by importing it on DFN codes.

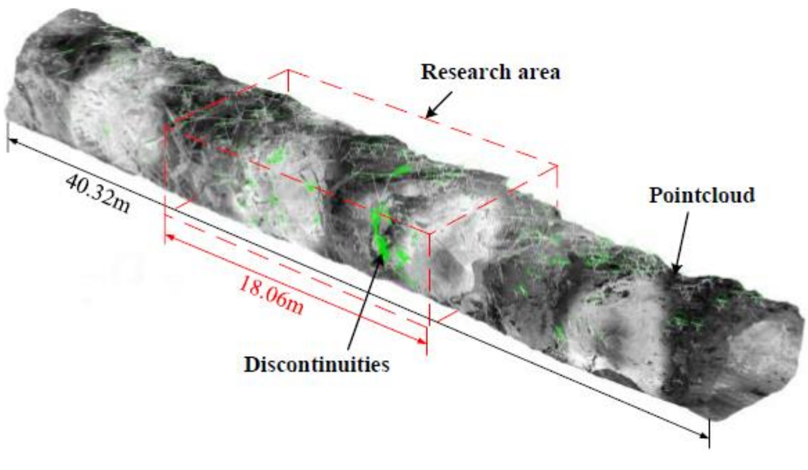


Figure 9. Three-dimensional point cloud data of an underground mine (adapted from [100]).

Similarly, Graaf [101] applied the DFN approach to accurately generate the 3D fracture network geometry of the Callie underground gold mine, which is used to develop a guideline to assist geotechnical engineers to know the variability and how the rock mass will behave under different loading conditions.

Moreover, the DFN can be used as a tool to determine the block size and volume of the unstable key block during underground excavation. The key blocks are formed as a result of the intersection of joints. In a study by Starzec and Tsang [102], they applied probabilistic calculations of unstable blocks around a circular tunnel to develop a relationship between the volume of blocks and fracture spacing and fracture intersection density. The study applied the volumetric feature intersection density as a means of quantifying the effect of feature parameter estimates on block prediction. In another application in the underground mining environment, Rogers [79] used the DFN approach with photogrammetric data to examine rock mass movement in an underground excavation. Elmo [103] used the DFN approach to simulate rock mass behaviour and combine the effects of intact rock fracturing and failure occurring along the natural fractures. The approach entails the use of synthetic rock mass (SRM) modelling where the DFN serves as one of the three components of SRM. Esmaieli and Hadjigeorgiou [104] conducted synthetic rock masses of the four-rock mass domain which was developed in the DFN to investigate the influence-induced damage from the transiting material in a Canadian underground mine. Harthong [105] used a coupled DEM-DFN approach to characterize the influence of the clustering and size distribution of pre-existing fractures on the strength of fractured rock masses. The DFN was used to control water inflow into underground excavations during and after construction [106]. Water ingress influences the stability of underground excavation and can cause adverse environmental impacts, which can in turn influence the project schedule. The DFN was used to examine the possibility of water inflow into the underground excavation in heterogeneous fractured rock. Likewise, Li [107] used the DFN to investigate the impact of water seepage on the surrounding strata of the shaft, that is, the effects of pore pressure and water inflow on the shaft pillar stability. DFNs have been widely used in mining operations. Most especially in the area of stability analysis, the effect of water ingression and pore pressure on strata control, underground water flow in deep level mines, rock mass characterization, and slope stability in open pit mines.

5.2. Application of DFN in Petroleum Industry

DFNs have been extensively used in the petroleum industry to generate the stochastic realization of the fracture network. In oil and gas production, the description of the reservoir fracture network is one of the parameters to be considered in reservoir geomechanics and production performance evaluation. The data acquisition mode in the petroleum industry for the DFN is different from that of solid minerals. During oil and gas production, data are collected from wireline logs, convention cores, small drilling mud loss analysis, and field-scale observation from outcrop analogue inspection [108]. Fracture data such as types, orientation, distribution, and properties are used in generating the stochastic model of the fracture reservoir.

However, the DFN model is used in prediction flow characteristics, which is a robust parameter in defining the dynamic performance of a naturally fractured reservoir (NFR). In Karatalov's [109] study, the work presents applications of fracture characterization parameters such as fracture length, aperture, and intensity to carry out sensitivity analysis of NFR modelling. The outcome of the study showed that the top three parameters of the fracture network are prioritized in the following order: fracture aperture, upscaling method, and fracture intensity. Likewise, Mahmoodpour [110] applied the DFN approach to mimic the reservoir permeability. Based on the acquired field data, a stochastic DFN was developed to evaluate the permeability behaviour of the reservoir. The simulation showed that a large number of fractures are involved in the stochastic model, and equivalent permeability fields are calculated to create a model which is computationally feasible. Similarly, Gentier [111] developed models based on a realistic fracture network from hydraulic systems to simulate the fluid flow that takes place within the fracture. A DFN model was built from the data collected from well imagery and estimation of fracture density using the Fisher distribution approach with the four major fractures set that constitute the reservoir. To develop an effective and efficient shale natural gas well, the designer or engineer must have a clear understanding of the role of natural fractures in shale gas production. In most cases, DFNs are applied in the area of hydraulic fracturing of the rock formation to stimulate the flow of oil and gas into the wellbore. This hydraulic fracturing approach has been in use for over 60 years and has promoted the shale gas boom in the past decade [112]. The primary purpose of the hydraulic fracturing approach is to increase the oil and gas yield in the well. This is carried out by injecting large quantities of fluid (chemical additives, water, or proppant) at high pressure into the targeted rock formation. Several studies have proven that hydraulic fracturing causes an increment in oil and gas production. Viegas [113] applied the DFN to provide a detailed analysis to highlight fluid flow paths and proppant placement in a shale reservoir. The method was used to calculate both static and dynamic parameters such as the fracture plane orientation, moment tensor, seismic efficiency, radiated energy, slip direction, and dynamic and static stress drop. Likewise, Zhang [112] used the DFN model to investigate four different shear deformation mechanisms. Similarly, Wang [114] used the DFN to model a unified shale gas reservoir to examine how each mechanism influences shale gas production and the corresponding rate transient behaviour. In the event of a tight reservoir, the flow in a fracture obeys a different pattern. Wang [115] applied an open-source numerical code (ShOpen) which comprises stochastic fracture modelling, multi-continuum modelling, and discrete fracture models for simulations of unconventional gas reservoirs. The numerical code can measure the fluid flow, absorption, transport, and indirect hydromechanical coupling in unconventional fracture reservoirs, as shown in Figure 10.

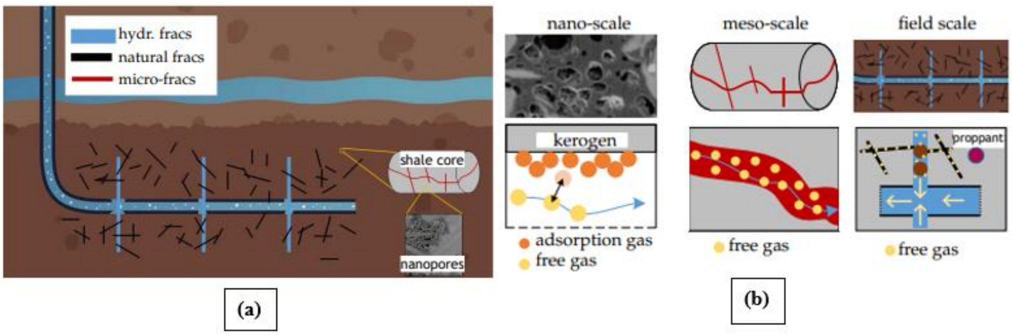


Figure 10. Description of shale gas production (**a**) gas transportation and (**b**) multiscale features (adapted from [115]).

Furthermore, the DFN is also applicable in geothermal projects. The understanding of fracture characteristics and properties is essential for effective geothermal reservoir management. A geothermal reservoir is a natural underground source of geothermal energy, typically consisting of hot water or steam often located near tectonic plate boundaries, where there is a high level of geothermal activity or in areas with a high concentration of volcanic activity. These reservoirs are formed when water seeps into the ground and is heated by the Earth's internal heat, whose temperature and pressure are dependent on the depth and geology of the area. Geothermal reservoirs are typically found at depths of a few hundred metres to several kilometres below the Earth's surface. Mahmoodpour [116] employed a DFN for modelling a reservoir and wellbore to simulate hydraulic and thermal processes involved in the geothermal energy extraction operation at Soultz Sous Forêts, France, with the aim to possibly extract higher amounts of geothermal energy from the existing industrial infrastructure. The validated hydro-thermal operational data were used for a numerical model to simulate the geothermal energy extraction operation for 3 years as a basis for the two operational scenarios for 100 years using four different injection wellhead temperatures of 70, 60, 50, and 40 °C. Mahmoodpour [116] asserted the feasibility of 100 years of geothermal energy extraction operation at Soultz-sous-Forêts with sufficient high-production temperature throughout the operation's duration.

Reservoir flow modelling technology was used to assign a constant heat flux at the bottom of the boundary of the domain while all boundaries were defined as no flow for both fluid and heat transmission. Discrete fractures within the domain were regarded as internal boundaries, implicitly considering the mass and energy exchange between the porous media and fractures or fault zones while the diameter of the injection well is represented by a line for simplicity. One of the earlier applications of the DFN in geothermal projects was recorded by Tester [117] to replicate the reservoir permeability behaviour. The outcome of their study stated the importance of creating a connected network of pathways between the injection well and production in a petrothermal system that lacks sufficient natural fluid flow and permeability for flow rates required for economic geothermal systems. These reservoirs' enhancement was achieved by creating new fractures or simulating naturally existing ones to achieve the permeabilities needed for economical fluid flow.

In a study by Aydin and Akin [118], the DFN model was used to create the fracture geometry, conductivity, and connectivity and to construct fracture networks that were instrumental to the characterization of the Alaşehir geothermal reservoir which is comprised of highly fractured marble and schist. Other fracture parameters that were considered in the fracture modelling include fracture permeability, aperture intensity, and fracture radius. Jambayev [119] constructed a DFN model for a free well section of naturally fractured "Field X" to improve reservoir characterization and to accurately predict the flow rate for the carbonate reservoir. Several researchers have performed fluid flow calculations by upscaling the DFN to an effective continuum model [120].

5.3. Application of DFNs in Tunnels and Underground Construction Works

DFNs are widely used in civil engineering projects such as tunnels, shaft sinking projects, and the construction of roads. A basic understanding of how fractures are distributed on a rock mass is important during the construction of underground projects, that is, the formation of key blocks and shape and size characterization are the fundamental properties and parameters to be considered in the engineering analysis of fractured ground. Although, for robust design, the strength of the rock mass, deformability properties, and permeability behaviour of such ground are also put into consideration. Moreover, the stress field conditions can also influence the stability of the tunnels and underground constructions. These parameters and point cloud data from laser scanners during field observation are used to develop a DFN model which highlights the area that needs a support system. It also provides tools to evaluate the stability of grounds around the excavation area, as the DFN would generate a model that represents the fracture geometry.

However, the application of DFN models in a tunnel is carried out by acquiring data from joint surfaces to create digital sections of the mapped area. The common method used to extract the plane orientation data and to determine the dominant joint sets from identified discontinuity planes is the use of polyworks [121]. The approach states the statistical sample of the joint dip and directions value can serve as input parameters for numerical modelling computer packages such as Dips from Rocscience. The exported data from the polyworks contain the original coordinates of the tunnel, which may not be linear but contain irregular geometry. The DFN technique has been applied by various researchers to solve geomechanical problems in civil engineering and stability analysis of underground construction projects. In Cacciari and Futai's [121] study, a computational approach for generating single and continuous DFNs was developed and applied to 324m of Monte Seco tunnel with foliated gneiss formation from Nova Venecia complex in Brazil. The result confirmed that it is possible to evaluate the variability of P_{32} (volumetric intensity). Notably, the variability of rock face orientations in the tunnel was considered by comparing the P_{32} results and taking the highest value as a reference for each tunnel sect. In Wang's [122] study, a larger convergence area was obtained in the circular opening model due to the effect of the fracture sets. Similar fracture patterns observed around openings with structural planes are shown in Figure 11. The DFN models created were able to provide a comprehensive overview of the rock mass behaviour which is used in predicting the stability and mechanical response of the ground condition to discontinuities present. The authors used a novel rough discrete fracture network (RDFN) characterization method based on the Fourier transform method. The outcome of the numerical simulation of the anisotropic mechanical properties was performed for the RDFN model with a complex joint network. Based on the results, the geometry of the joint network has a significant influence on the strength and failure patterns of jointed rock masses.

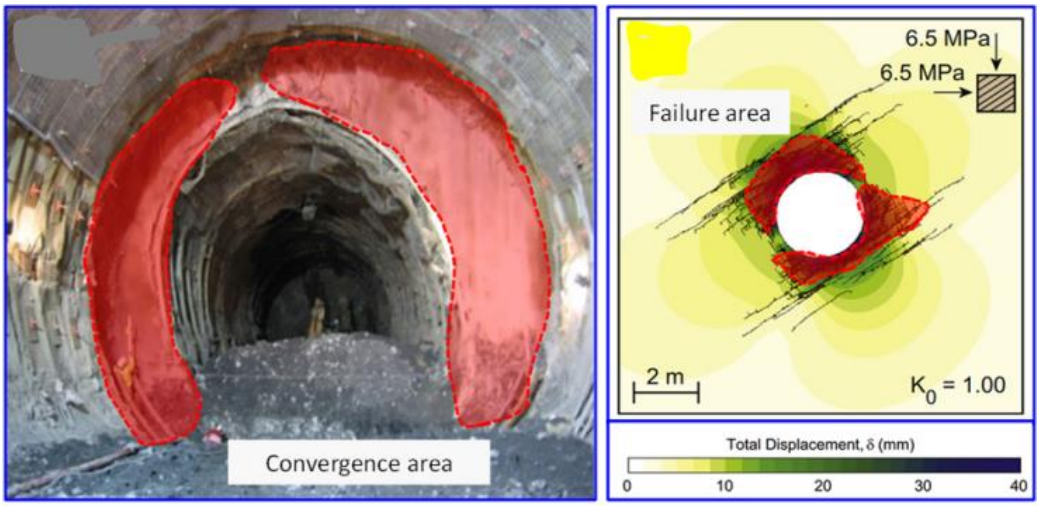


Figure 11. Construction of tunnel face from fracture pattern around circular openings (adapted from [122]).

Similarly, Ioannis [123] used a hybrid approach of both deterministic and statistical techniques to generate a DFN based on available data to simulate the rock mass behaviour and stability analysis of the Brockville tunnel in Ontario, Canada. Data from laser scanning data were used as input parameters in Morfa DFN software to construct the specific tunnel site.

5.4. Application of DFNs for Underground Flow Prediction

The presence of fractures plays an important role in the flow of fluid through the rock masses. The interconnected fracture network influences the channel flow which was developed through the conductivity of existing fractures or by new growth that connects existing fractures. The DFNs are used in modelling flow and fluid movement in the subsurface. The model is developed to simulate the movement of flow underground structures through interconnected fractures. This approach has been widely used in geoscience and engineering to control the movement of fluids such as in groundwater management, geothermal energy extraction (Saliu and Komolafe [124]), the aquifer recovery process, hydrocarbon extraction, carbon sequestration, and radioactive and toxic industrial waste [125]. Primary factors affecting groundwater flow include fracture density, fracture orientation, aperture width, and the rock matrix. According to Bordas [126], the fracture density and the fracture orientation are the most important parameters that define the interconnectivity of a fracture set, which are the contributing features of the hydraulic conductivity of a fractured rock mass. Moreover, this serves as vital input parameters for simulating the 3D representation of the subsurface fracture geometry. The fracture model created by the DFN describes the flow of the substance using data collected to characterize the fractures that influence the transportation and free flow of the substance. The main challenge of using the DFN for underground flow simulation has been the choice to include a detailed geometrical representation of the fracture and their respective fracture connectivity that is used in the predictive simulations of fluid flow in fractured rock. This makes it difficult to design an efficient and scalable workflow. If a well-defined fracture geometry of the rock mass can be acquired, the 3D representation of the subsurface fracture network can be determined. Moreover, the in situ stress and change in stresses of the rock mass have a significant influence on the flow, as this will cause changes in pore pressures within the rock mass.

Moreover, another common application of the DFN in underground flow is the evaluation of contaminated water-bearing rock. Contamination of groundwater flows occurs majorly at abandoned sites (Saliu and Komolafe [124]), where the fluid flows and where most contaminated mass flow occupies the much lower permeability matrix block between fractures [127]. The contamination of the fracture takes place when contaminated substances diffuse from the fracture where active groundwater flows occur into the permeability rock matrix. In traditional methods of investigating contamination, the rock matrix is disregarded as most of the fracture's active flows are ignored. The lack of data from borehole core sample contamination data makes it difficult for the conventional approaches to characterize the plume in a fractured rock mass. On the other hand, the DFN approach makes use of data from core rock samples from the subsurface to delineate the diffusion of contaminants on the fracture network. According to Parker [128], the application of the DFN method in this event is designed specifically for sedimentary formation, although it can work for all other rock types but must be adjusted to suit the nature of the matrix porosity, absorption rate, contaminant type, and time for diffusion.

5.5. DFN Application in the Classification of Rock Mass

The classification of rock mass is important for any engineering design The understanding of rock classification improves the quality of geoengineering designs as the geotechnical engineer will be provided with quality design input parameters [129–131], that is, the fundamental understanding of geological, structural, and mechanical classifications of the rock mass is required at the planning stage of excavation in mining and civil engineering projects. The classification properties of the rock material and the joint properties should be considered in the design. The result of the rock mass classification enables better engineering judgement most especially in underground construction when the subsurface fractures are not known. The absence of a true 3D representation of subsurface fracture geometry might be a challenge. The better the understanding of the fracture geometry of the rock mass, in quantifiable terms, the less the variability that needs to be considered in the input parameters for the classification. The DFN has the potential to describe the 3D representation of fracture geometry located in a rock mass in the subsurface, that is, the DFN model defines the geometrical properties of an individual fracture and its topographical relationship with the geological structure. For instance, a tunnel with a certain rock mass with a widely spaced geological structure may be unaffected by the structure, but the behaviour of an open stope in the same rock mass may be influenced by the jointed rock mass condition and major structural features such as faults.

The DFN arises to be an interesting tool in classifying rock mass structures. The data can be collected from the borehole core samples to produce the in situ fracture network. Since the DFN model can generate the in situ conditions of the subsurface rock mass, it is therefore important to continually update the DFN geometry as the excavation advances. The DFN approach has been widely used to simulate the classification of the rock mass. The method applies statistical and spatial measurement to examine the rock properties that determine the behaviour of the rock mass. The aim of the fracture geometry classification by DFN is to provide some geotechnical information that could be used for satisfactory planning and mining of safe excavations. It is critical to understand the variation in the properties of the rock mass, most especially in a deep underground mine where the properties of the rock mass change with depth. For instance, the DFN model can highlight the strength variation in rock mass from a small and strong intact specimen to a relatively intense fracture large slope [90].

6. Challenges of Using DFNs

DFNs have in recent times proved to be one of the veritable tools employed for geomechanical analysis for solutions in mining, geotechnical engineering, borehole mapping, and various applications in petroleum industries. Despite its versatility, there are still some limitations and challenges to the integration of complexities encountered in rock masses within DFN models. The inherent occurrence of geological discontinuities, such as joints, faults, shear zones, schistosity planes, and bedding planes [131], complicates the failure process observed during laboratory-scale experiments in comparison to the failure within the rock mass. As a result of these intrinsic uncertainties, the application of numerical modelling to the analysis of rock engineering problems poses a challenging task due to these discontinuities [132].

Most often, homogenization models are not a true representation of the real rock masses. For instance, in an underground cavern's rock mass deformation and failure analysis performed with a numerical tool for a blocky jointed rock mass, some pseudo-DFN models generated to simulate the joints in the rock mass explicitly having multiple joint sets, and many loose blocks are formed at the excavation boundary, making the cavern unstable; hence, the model does not converge. To stabilize the jointed model, supports are installed at the same stage as the excavation. This will underestimate the support capacity of the bolts and liners; hence, low deformation can be seen on the excavation boundary as expected in reality. As the k ratio increases, the induced stress on the crown pillar increases, creating a large deformation along the roof and floor. Martin [132] attested that 2D elastic analysis does not account for the effects of stress redistribution as failure progresses, which may be a result of discontinuities coupled with the kinematic constraints on the deformation and failure modes of structures in rocks [133] and causes stress and displacement redistributions to sensibly deviate from linear elastic, homogenous conditions [134]. Moreover, in all the model simulations, the maximum total displacement of the jointed model is always higher; hence, more robust support systems are required to stabilize the cavern along with the real-time stress and load monitoring in the field. It is therefore imperative to find a proper set of working plans and sections where a "creative thinking" process was applied, and geological and geotechnical concepts are tested prior to computerization [135].

Karimi and Elmo [136] stressed the need to improve engineering designs by integrating DFN numerical models within the geomechanical codes. There are challenges in coherently optimizing fractures in 3D and traces in 2D of the initially generated DFN models to minimize meshing issues while preserving the appropriate model's properties. The reliance on mesh sizes in continuum and discontinuum modelling methods dictates the mode and the types of failure mechanisms that are visible for capturing, and this must also be considered in the selection of the required input material parameters, which would depend on the degree of simplification adopted when building the model and the choice of a continuum or discontinuum model [137]. This limitation may occur due to inappropriate consideration of the subsequent mesh generation routines that are necessary for geomechanical simulation [138]. Considering the geometrical complexities of DFN conceptualization arising from many discontinuities intersecting with each other, there must be a compromise between mesh quality and the minimum element size, and this largely depends on the experience of the user for correct interpretations of how to correct or modify some specific discontinuities.

Of paramount interest to mining engineers in underground mine design is pillar strength, and this largely depend on the determination of rock mass strength with precision [55]. A more realistic depiction of the discrete fracture systems is required to accurately simulate the mechanical behaviour of mine pillars by numerical modelling [139]. There are challenges which may arise as a result of inadequate estimation and classification of the rock mass damage as a function of natural fracture network and loading conditions [135]. The accuracy and the inclusion of an impact of block to structural damage with respect to the initial block may not be properly accounted for as dilation in some models. Traditionally, there is an assumption that blocks are orthogonal, having mean volume, but the dissimilarity in joint conditions such as spacing, infillings, and orientation in the natural rock mass makes it rare to have an orthogonal block shape [140]. Effectively obtaining the size, shape, and other relevant block information of the exact blocks contributing to the structural damage is needed to define the relationship between the structure-damaging blocks and their parent blocks at the initial timestep for better investigation [135].

7. Summary and Conclusions

Fracture networks play a pivotal role in the quest to harness the critical minerals within the Earth system, hence the development of the DFN using various data-capturing methodologies and different computer programming codes for numerical modelling to enhance safe, smooth, economical, and sustainable exploitation of such minerals. The authors logically reviewed the recent advances in conceptualization of the DFN and its various engineering applications in the areas of mining, geotechnical engineering, borehole mapping, and petroleum industries.

The concept of the DFN model hinges on creating networks that replicate the major structure of the mapped rock mass using the data acquired during the site investigation while considering the geological structure of the site, the scale, and the purpose of modelling. The authors classified these data into fracture orientation, intensity, spatial location, and fracture size. The statistical method and probability distribution approach based on the principle of the von-Mises for 2D and the Fisher distribution and uniform distribution for 3D are used to represent fracture orientation (attitude of a discontinuity in space which measures the dip and the dip direction of the joints) using the data emanating from the outcrop measurement or well logging. Fracture intensity, which is the surface area of discontinuities per unit volume, plays an important role in determining the mechanical properties and hydraulic conductivity of a discontinuous rock mass, and this can be quantitatively determined by fracture tensor. The size and length of fractures in the DFN model, which are used to characterize fluid flow in fractured rock masses, were quantified by empirical and back analysis approaches before the advent of some modern advances in DFN modellings were developed to ease the process of delineating fracture size and length.

It has been established that the quality of the input data determines the outcome of the fracture network. The acquisition of a huge amount of data within a short period of time by modern data-capturing technologies has tremendously improved the solutions provided by DFN models for various applications. Besides the accuracy of the huge data captured, the advent of these cutting-edge technologies has brought about the introduction of digital mapping instruments such as the terrestrial laser scanner, borehole televiewers, and photogrammetry, which can generate high-density 3D point cloud data from rock surface mapping.

The institution of a DFN as solutions to many challenges, which in the past were unsurmountable in the mineral industries, has become one of the major technological innovations in recent times. Its versatility and flexibility made it a useful tool for advanced engineering analysis that requires the evaluation of fracture geometry in jointed rock masses. Its application in mining includes but is not limited to the stability of the fractured rock slope, coal seam longwall face, underground excavation, and investigating the possibility of water inflow into the underground excavation in heterogeneous fractured rock. In the petroleum industries, the DFN is applied in the area of hydraulic fracturing of the rock formation to stimulate the flow of oil and gas into the wellbore and to accurately predict the flow rate for the carbonate reservoir. The DFN also finds its wide expression in the civil engineering projects such as tunnels, shaft sinking projects, rock slope stability along highways, and the construction of roads. Ultimately, these applications are hinged on the accuracy of the rock mass characterization using the DFN models. The result of the rock mass classification enables better engineering judgement, most especially in underground constructions when the subsurface discontinuities are not known.

Despite the versatility of the DFN, there are still some limitations and challenges to the integration of complexities encountered in rock masses within DFN models. It cannot be convincingly said, however, that a model is a perfect imitation of reality, particularly at the initial stage when data availability is limited. For instance, forward modelling results cannot be said to be calibrated and validated at the prefeasibility or feasibility stage if the final shape of the stopes or caverns remains unknown. One of the greatest modelling challenges in caving geomechanics is the ability to develop a 3D caving model capable of incorporating fracture mechanics principles and other failure mechanisms to explicitly simulate fragmentation processes at the level required to depict secondary fragmentation while also maintaining a detailed representation of the rock mass structural physiognomies and replications of preconditioning scenarios [137].

The quest for valuable mineral resources to satisfy human wants, especially those identified in critical minerals lists for sustainable and economic success, has given rise to technological development in the mining industry. It is therefore necessary to develop technologies that can extract complex ore bodies with lower grade, at deeper depth, and sometimes in the challenging geological formation which necessitates the extension of life of the mine. These feats are made possible by the improvement of DFN models and their proper applications.

Author Contributions: Conceptualization and Manuscript Writing, P.K.; Manuscript Writing and Editing, N.O.O.; Review and Manuscript Editing, P.M.; Manuscript Administration, D.A.; Conceptualization and Manuscript Writing, K.K.; Manuscript Editing, A.G.-B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

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