Multidimensional Flow Modeling using Discrete Fracture Network (DFN) in Fractured Rocks

A dissertation submitted in partial fulfillment of the

requirements for the award of the degree

of

MASTER OF TECHNOLOGY

in

HYDROLOGY

By

ABHISHEK KUMAR

DEPARTMENT OF HYDROLOGY
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE- 247667 (INDIA)

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in this Report, entitled *"Multidimensional Flow Modeling using Discrete Fracture Network(DFN) in Fractured Rocks"* in partial fulfillment of the requirements for the award of the Master of Technology in Hydrology, submitted to the Department of Hydrology of the Indian Institute of Technology Roorkee, India, is an authentic record of my work, under the supervision of Dr. B. K. Yadav, Associate Professor of the Department of Hydrology, IIT Roorkee.

The matter embodied in this report has not been submitted by me for the award of any other degree.

……………………
(**Abhishek Kumar)**
Enrollment No. 16537006

CERTIFICATE

This is to certify that the above mentioned statement made by the candidate is correct to the best of my knowledge.

…………………
(Dr. B. K. Yadav)
Associate Professor
Department of Hydrology
Indian Institute of Technology
Roorkee
India


भारतीय प्रौद्योगिकी संस्थान रुड़की
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE

ABSTRACT

Fluid flows through complex network of fractures in a fractured rock mass. Equivalent porosity model approach is conventionally used for flow simulation through such types of porous media which considers fractured rock as a single porosity system where every fracture contributes to flow.However, fracture connectivity which affects flow pathway significantly is ignored in such types of simulation. The other modeling approach like dual porosity/permeability considers rock masses as mobile-immobile media considering fracture network as a highly permeable media and surrounding porous matrix as an immobile domain. But these methods require more detailed input data information for their development. Also the entire study domain is considered as a whole, including the soil matrix and fractures, for such types of models. Thus in this paper, DFN approach is followed to simulate the water flow through a fractured rock mass by considering each fractures individually and has flexibility of modeling using deterministic and stochastic approaches. As it is not feasible to map fracture networks in rock masses because accurate field measurement of single fracture is difficult, deterministic approach is rarely applicable in field. On the other hand, stochastic method uses data collected from rock outcrops, drill cores, borehole imaging, satellite imaging, geophysical surveys. Therefore, stochastic modeling of discrete fracture network is adopted here for modeling fracture locations, geometries and their orientation by respective probability distributions. Data required for discrete fracture network modeling are maximum and minimum fracture length, fracture orientation, and total number of fractures. FraNEP software which evaluates fracture length by applying power law equations using cumulative distribution functionand plots fractures orientation is used in this study. The simulator also classifies fractures into different sets according to their orientation which are used in further modeling stages. In addition, it also provides information like fracture density, intensity and their mean length. After creating fracture network model using DFN, all fractures are converted into pipe model using the Polygon method. Flow simulation is then performed by applying finite difference method for obtaining output in form of variation of pressure head across the connected fractures in multi-dimensional domain. The developed modeling approach is applied well to Jabal Akhtar dome in Oman mountains. Findings of this study are of direct use in predicting accurate flow and solute transport through fractured porous media at field scale level.

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Abhishek Kumar

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Chapter1: Introduction

1.1 General:

A fracture is defined as a discontinuity within a rock mass (Priest 1993). The term fracture thus includes faults, joints, fissures, cleavages and even discontinuities between mineral particles. A fracture can be on a scale of a few microns to several kilometers (e.g., faults). Engineering-scale fractures are generally greater than 10 cm and less than 1 km (Odling 1991). Fracture is considered as an empty space between two parallel planes embedded in a rock mass with the spacing between the two planes termed as aperture (Kacewiz 1994). Even a simple fracture network of rock mass can contain hundreds of fractures of different sizes and orientations. Intersections of fractures are extremely complex but for fluid flow through rock masses fracture intersections are the critical control points (Hayashi et al. 1999).

A number of methods are present to model flow through fractures in rock mass like equivalent porosity model (Alshawabkeh 2015) which treats fractured rocks as homogeneous system. These models do not consider effect of connectivity of fractures in fluid flow, instead they approximate the overall local conductivity of the matrix and fractures. Other models which are widely used for flow simulation in fractured rocks are based on dual porosity/permeability approaches (Wu and press,1988) which treat fractures and matrix as two different porous media as shown in figure 1.1. This modeling approach has limitations like over homogenization of characteristics of individual fracture (Reeves et al.2014), negligence of complex pattern of fracture connectivity (Liu et al.1998) and meshing of fractures and matrix which is cumbersome and time taking (Singhal and Gupta,2010).

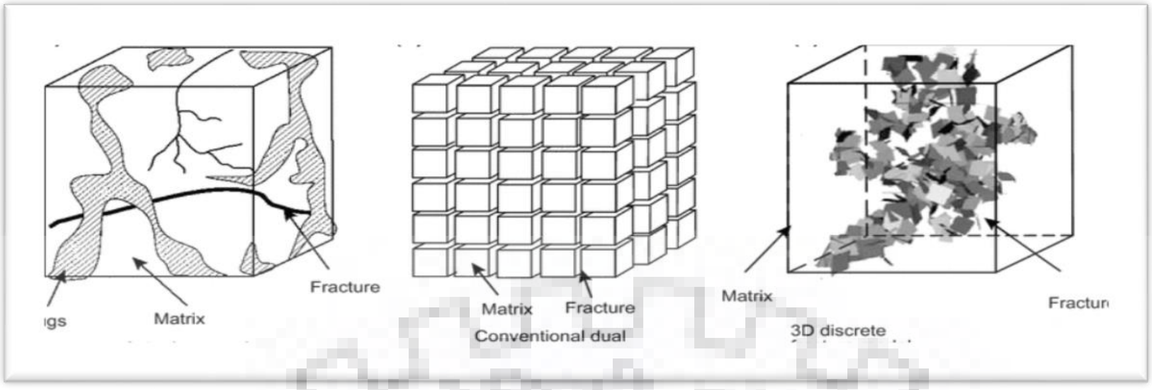

Figure1.1: Schematic of fractured rock mass used in Dual porosity/permeability models and in DFN model (Biryokov and Kuchuk,2012)

A mathematical model (Chernoutsan et al. 2011) is usually used to describe the most significant governing features of fracture networks (Dimov et al. 2011). If such an assessment is based on modelling of individual fractures the method is called Discrete Fracture Network modelling (Jing 2003) as opposed to continuum modelling in which the entire system is modelled as one continuous domain. For modeling the complex geometries of fractures and their connectivity, discrete fracture models are more suitable and specially for rock mass where matrix block has very low permeability and flow is mostly through fractured rocks (Jafari and Babadagli 2012). In DFN, permeability of rock matrix is assumed negligible and flow takes place predominantly through connected fractures (Liu et al.2016).

DFN modeling can be done either using deterministic or through stochastic approaches. Deterministic approach which is quite common in solving engineering problems requires fully defined domain and its associated parameters for the well-defined governing equations to result in useful and accurate outputs. The level of accuracy in these model inputs directly affect the model output with even much higher loss of accuracy due to accumulation of errors including approximation and numerical errors. In fractured rocks, it is difficult to obtain all parameters of fracture, such as location, size, orientation and spacing between fractures (chiles and de marsiley,1993) and thus stochastic approach for flow simulation in fractured rock is more suitable as compared to the deterministic approach. Stochastic approach uses applied statistics and probability to tackle the issue of lack of sufficient data. Stochastic methods have frequently been shown capable and efficient to model uncertainties involved in a variety of engineering problems and their prospective future applications are rapidly increasing.

Work has been carried out in past on stochastic DFN model like to predict the fluid flow and transport properties. stochastic DFN model was prepared to simulate fluid flow in fractured rocks from the Fanay-Augères uranium mine (Cacas et al. 1990). The authors assumed negligible permeability of rock matrix and fluid flow was considered through fractures only. Similarly, a stochastic approach was used to evaluate the permeability of fractured rock (Min et al.2004). Another study was presented by Cvetkovic and Haggerty (2002) where DFN model was generated using Monte Carlo simulation and fractures were converted to pipe network to simplify the flow simulation.

Most of the studies related to fractured mass used deterministic method to calculate fracture characteristics which is time consuming. Studies on flow simulation using DFN were completely stochastic in nature which saves time that field investigation for determining fracture characteristics. This approach requires large number of fracture simulation to be performed to replicate fracture characteristics on field by taking random values of fracture geometry such as fracture length, and its orientation. Therefore, in this study; FraNEP simulator is used to calculate fracture characteristics using a mixed approach of stochastic and deterministic modeling. Trace line map obtained from satellite image has coordinates of fractures which is used as input in FraNEP. This simulator provides characteristics of fractures as output. Fractures are then modeled using stochastic approach. Thus a combination of stochastic and deterministic method saves time and there is more chance to resemble real fracture network at field level.

DFN is more flexible (Dershowitz et al. 2000) in dealing with the complex fracture configurations observed in practice using a stochastic solution where the distribution of fractures is often sparse and there is also significant uncertainty involved in measurement of fracture and fracture network parameters; thus deterministic methods such as finite techniques (e.g., finite element (FEM), discrete element (DEM), finite difference method and so on) cannot solely handle those situations although they are well-known and well-developed numerical modelling techniques and are applied to variety of engineering problems. Thus, in this paper, stochastic approach to Discrete Fracture Network Modeling is adopted and is applied to simulate fluid flow in Jabal Akhtar dome in Oman mountains to study movement of fluid to groundwater. For simplification in flow simulation, fractures are converted to pipe model by connecting fracture centers with fracture intersection point. Data acquisition for fracture network modeling is obtained by studying trace line map obtained from satellite image using FraNEP software.

1.2 Objective

The main objective of present study is to simulate water flux moving to underlying subsurface of fractured rock using DFN modeling. The specific objectives of this study are:

1. To understand flow through fractured rocks using discrete fracture network method.
2. To generate statistical properties of lineaments, present in a fractured rock of Jabal Akhtar dome in Oman mountains using FraNEP software.
3. To develop MATLAB functions for creating 2D and 3D fracture network model.
4. To convert fracture network model to pipe model and show flow pathway in pipe model by removing unconnected pipes.

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1.3 Organization of Dissertation:

Chapter 1 – General introduction of fractured porous media is presented along with different models available for simulating flow in fractured rocks is presented here. Advantages of using Discrete Fracture Network model over other models is mentioned here along with a brief overview of studies conducted in past using DFN. Merits of stochastic method over deterministic method is also provided before mentioning the objectives of this dissertation.

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Chapter 2 – Literature review pertaining to flow through fractured rocks is mentioned in Chapter 2. Different probability distribution functions are described which are popularly used to simulate multi-dimensional fracture network models. Research work carried by different authors on flow simulation using different modeling approaches is also briefly presented in this chapter.

Chapter 3 – Methodology used to simulate fluid flow in fractured rock is presented in this chapter. Overview of study area along with the methodological framework used to study trace line map generated from satellite image is described here. Fracture characteristics evaluated from trace line map and associated preprocessing operations are mentioned in detail. Methodology by which fracture model is converted to pipe model is also presented in this chapter.

Chapter 4 – Results obtained using FraNEP simulator are described in this chapter along with the outcomes of trace line map and details on fracture geometry used to create fracture model is presented here. Details of flow pathway and pressure head distribution in fractured rock is also presented in this chapter.

Chapter 5- – Conclusion of this work is reported in this chapter 5. Future work that can be done using DFN model along with limitations of this study is mentioned in the last section of this chapter.

Chapter 2: Literature Review

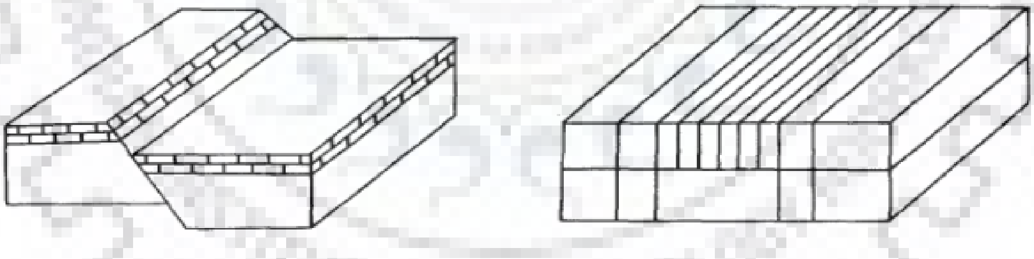
Overview of Fractures is provided first along with fracture properties of rock masses. Literature review pertaining to flow through fractured rocks is then mentioned followed by description of different probability distribution functions which are popularly used to simulate multi-dimensional fracture network models. Research work carried by different authors on flow simulation using different modeling approaches is presented in last along with the advantages of using DFN approach.

2.1 Fracture Overview

A fracture can be defined as any discontinuity within a rock mass that developed as a response to stress. The following two types of fracture are visible in natural rock system as shown in figure 2.1.

a) *Faults*- If relative displacement has occurred between fractures, then it is called fault.

b) *Joint*- If there is no relative displacement between fractures, then it is classified as Joint.



Fault Joint

Figure 2.1: Schematic representation of Fault and Joint

Fractures exist on a wide range of scales ranging from microns to hundreds of kilometers. These fractures have a significant effect on fluid flow in fractured rock, stability of rock (Bonnet et al.,2001). Highly fractured rocks can make good aquifers or hydrocarbon reservoirs as they poses significant porosity and permeability. A fracture can be defined in a geometrical three dimensional space with the following basic geometrical parameters as shown in Fig. 2.2: 1) dip angle 2) dip direction 3) dimension, shape and aperture (the gap between two opposite surfaces of the fractures). Although there are other properties that can define a fracture but these are the basic properties that can be used to define a fracture mathematically (Jing and Stephansson, 2007).

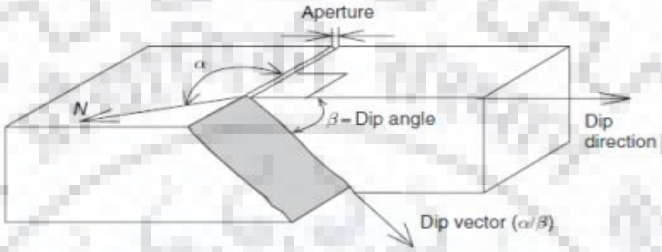


Figure 2.2: Geometric parameters associated with a fracture

Fractures are three dimensional geometric entities which are complex in the size for each individual fracture and the way they are scattered in space (spatial formation). Pattern of fracture locations, or fracture network dispersion pattern (Baddeley et al. 2006), is associated with the stress regimes in rock mass. The stress regime is formed due to physical, mechanical, chemical and other governing processes in the system. Other attributes are orientation, size (~length), shape, aperture, roughness. These features are basic geometrical and spatial features describing the system of fragmented rocks. Fractures network in fractured are modeled so that a realistic and reliable picture of the system can be obtained that can improve our understanding of fluid flow in fractured rock. Therefore, the geometry of the fracture network is an important factor in describing the whole system in such way that they closely define the behavior of fracture networks against the event such as fluid flow through network.

2.2 Fracture properties

There are several parameters associated with fractures for describing its property. Important properties which are used in mathematical modeling of flow through fractures are mentioned below.

Fracture Density: Fracture density is the number of fractures per unit area or volume (Davy et al., 1990). Fracture density expresses the extent of rock fracturing.

Fracture Length: Fracture length, i.e., the length of the fracture, Fracture length distribution is generally taken to be a lognormal.

Fracture Aperture: Fracture aperture also called the fracture width is the distance between the fracture walls (Bonnet et al., 2001).

Fracture cluster: A fracture cluster is a group of linked fractures. A cluster that links opposite sides of the study is termed a "percolating cluster."

Fracture Intensity: Fracture intensity of a fracture set is measured either by the number of fractures per unit area or the summed lengths of fractures per unit area (Ghosh, 2009).

Fracture Network: A fracture network is generally defined as a set of individual fractures which may or may not intersect (Adler et al., 2009). It can also be defined as formed by two or several associated fracture sets.

Fracture Orientation: Fracture orientation gives the direction and tilt of the fracture. When characterizing the fracture orientation distribution, it is generally found that the fractures can be divided into a number of distinct fracture sets. These sets of fractures comprise fractures that can be characterized by common distributions of parameters, and which have a common origin and history. Fracture orientation can be represented by rose diagram or using stereographic map. Fisher Distribution (Dershowitz et al., 2005) is the best method for statistical analysis of fracture orientations.

Fracture Spacing: Fracture spacing is the average distance between parallel regularly spaced fractures. It is the distance between two adjacent fractures of the same set following the same distribution function for their orientations.

2.3 Modeling Approaches of Fractured Mass

Fracture networks are very complex in geometry and topology. To model fracture network and perform flow simulation, advance techniques are required. Geometrical modeling of the fracture can be directly done using by pixel-based simulations (Deutsch 1998) or Voronoi tessellation simulations. In these methods, there are strong dependency between fractures and the resulting topology (Jing 2007a). In Voronoi tessellation, fracture connectivity defines network topology and once Voronoi cell is created, all locally associated fractures are produced concurrently. A different method is to generate all fractures independently and then generated fracture are located in space and then the associated topology is established. The latter is known as the discrete fracture network modelling (DFN, Jing and Stephenson 2007b). It is widely used and well developed method. There are basically three methods for fracture modeling that is commonly used to model fluid flow in fractured rock.

Equivalent porous media

Fragmented reservoirs are visualized as single potential model in equivalent porous media. In this model it is assumed that fracture network will distribute flow like porous media Rock matrix and fracture have different flow condition but in this model, it is assumed that there is no distinction between two flow states and properties such as conductivity and permeability are given importance There is no focus on individual discretization of fractures and only focus on interpretation on hydraulic properties of fractures.

Dual permeability model

Dual-permeability model (DK) is another approach in which both fracture networks and matrix participate in fluid flow compared to the DP model. The model is poorly suitable for average fractured reservoir. Gravity drainage can be simulated to limited extent and its computational cost is expensive.

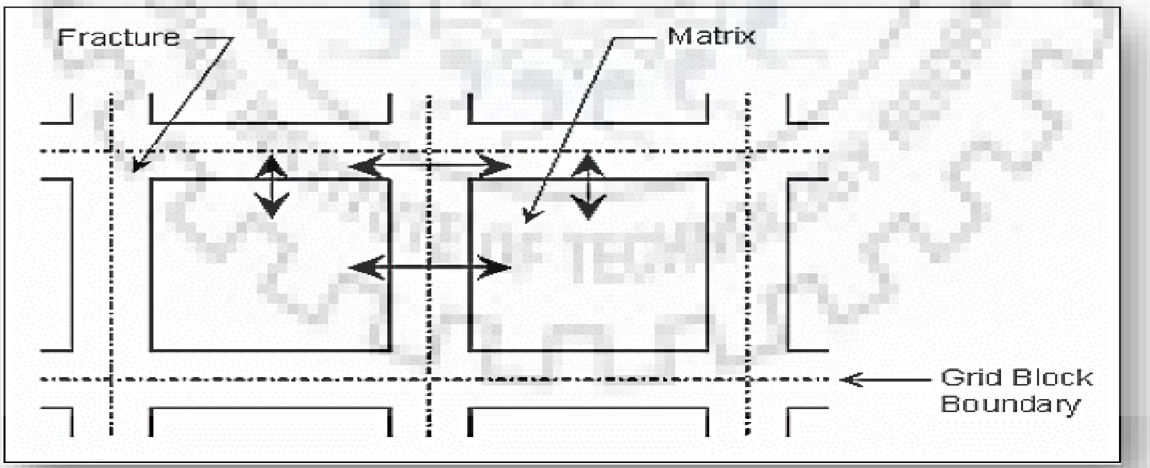


Figure 2.3: schematic representation of flow in dual permeability model

Dual porosity model

It is a more conventional method for depicting behavior between fractures. In this approach, fluid storage is mostly contained in porous matrix of rock and matrix hole is far larger than fracture hole and matrix is represented as orthogonally connected plane and it is assumed that fluid flow is only via fractures. There is no interlinking between immediate matrix and connection or flow between matrix is only through fracture flow. It provides accurate representation of flow in fractured reservoirs. But it has certain limitations such as there is no emphasis on effect of fracture geometry on fluid flow. This model does not consider the effect of gravity drainage on fluid flow as fractures and matrix are considered at same depth.

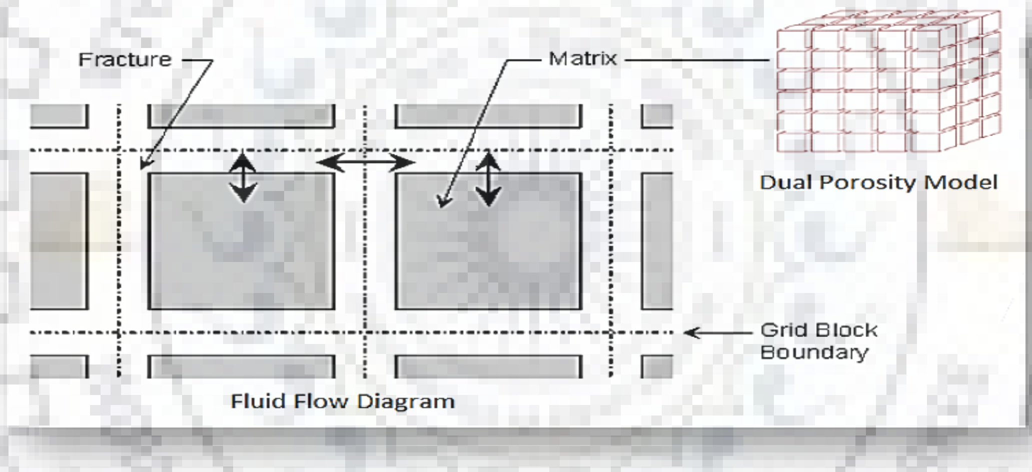


Figure 2.4: Orthogonally connected fracture and matrix block in dual porosity model

Discrete Fracture Network(DFN) Model

The fourth modeling approach is Discrete Fracture Network modeling; which is more recent method and it is based on assumption that in fractured rock, flow takes place through fractures only and rock matrix is considered impermeable. This approach of modeling is suitable for flow simulation through fractured rock mass where most of fluid flow occurs through fractures only. DFN are stochastic models that incorporate statistical functions for analysis of fracture length, Location, spacing, orientation, and aperture (Guohai, 2008). Studies on DFN can be traced back to the early 1980's. Researchers such as Noorishad et al.16 applied the technique. They investigated the pressure distribution along fractures using upstream Finite Element Method (FEM). Further enhancements for general petroleum engineering applications were made by Karimi-Fard and Firoozabadi. They used a Finite Element approach to avoid problems due to very small volumes of fractures compared to matrix blocks. Their DFN grid model used a Delaunay tessellation to align the block edges on the fractures. Aziz et al. aggressively worked on a general framework to apply finite difference discretization techniques to model the DFN more widely. He called the approach the Control Volume Finite Difference (CVFD). Pruess17 used a similar concept for geothermal applications and called the method Integration of Finite Difference (IFD). In DFN, fracture network geometry is defined using two methods: a) Deterministic modeling, b) Stochastic method.

Deterministic Method: In deterministic method, fracture network is modeled using accurate fracture location and orientation data which is collected from field investigation using technique such as bore hole logging, surface outcrop study, etc. Since the details of fracture network away from borehole or outcrop cannot be known, this method is not suitable for defining fracture network and subsequent flow simulation. This method is suitable for continuum model where fractures are homogenized.

Stochastic Method: Fracture characterization using Discrete Fracture Network (DFN) utilizes a number of statistical tools (fig. 2.5), the complexity of fracture networks means that a large quantity of data is required to characterize fracture network systems adequately. These tools aid in ensuring that the limited information of fracture geometry are applied well for flow simulation in fractured rock.

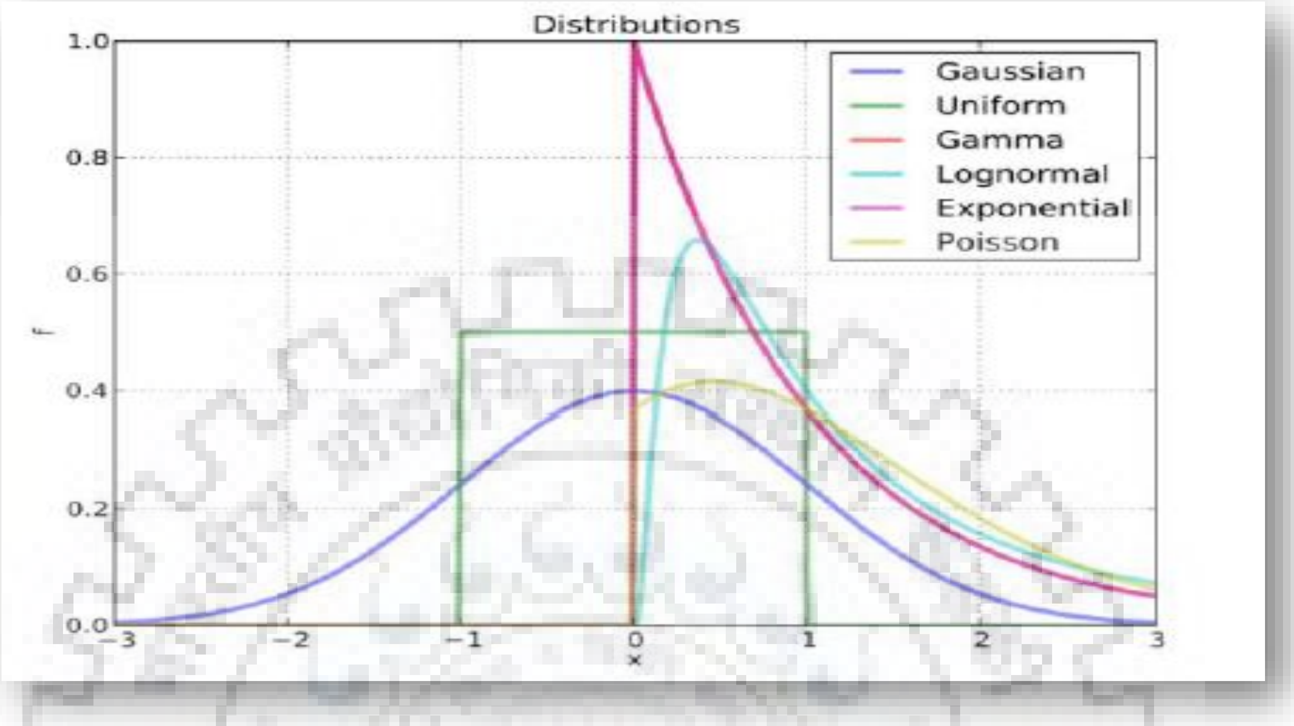


Figure 2.5: Commonly used distribution functions in fracture network modelling (Fadakar, 2013)

Using stochastic method means that fracture network model created cannot be similar to fracture network on the field. However, if one simulates many different realizations of the fracture network flow system, each having the same statistical properties as the real network, then the range of model results should bound the behavior of the real network (if a good statistical description of the fracture network has been used).

2D representation of fractures

On well logging (core and images), the sample of the fracture in two dimensions includes their trace lines (a plane that includes outcrops, tunnel walls) on the surface. The typical feature of this type of modeling is that the trace line is straight lines (often the finite line segment). Therefore, the third dimension of a real three-dimensional fracture, which specifically describes the shape of the dip and fracture, is not involved in two-dimensional modeling.

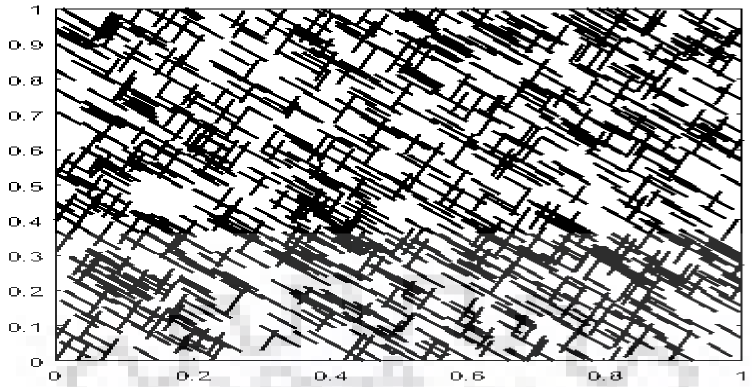


Figure 2.6: representation of fractures network as 2D using MATLAB in 1m*1m space of study area

This type of modeling is done when no three-dimensional measurement of the fracture system is available, for example, in the sample from surface outcrop in the field. Recent work by Renard (2011) reviews the lattice-based connectivity approach of fracture networks in two dimensional case. In two dimensional fracture network modeling, fractures are represented by the line segments, and to simulate fractures in two-dimension, determining location, length, and orientation characteristics are major challenges. Some assumption made to simulate fractures are a) length of the fracture is considered finite b) Orientation limited to two orthogonal directions, c) location is obtained from uniform distribution function. Locations are determined by Poisson point processes (Baddeley 2010) providing plenty of patterns including homogeneous, inhomogeneous dispersion patterns. Orientations follows von-Mises distribution. Lengths are obtained from power-law distribution functions including exponential and lognormal (Bour and Davy 1999).

3D representation of fractures

In three dimension, it is common practice to model fracture as flat plane. In the simplest cases, it is prepared as an infinite plane or in simple geometric shapes such as a circle or ellipse (Figure 3)

Figure 2.7: representation of fractures in 3D using MATLAB in 1m*1m*1m dimensional space

Another recent trend, however, is to model the fracture network as a set of polygon fracture, which is randomly positioned in space. Figure 3 shows fracture in the three dimensions with fracture in polygon shape. Polygon shape of the fracture is flexible and address the complexity present in fracture network (Figure3). Some assumptions are made before fracture network models are built like fractures are considered to be plane and each side of fracture surface is considered smooth. Aperture of fractures are very small compared to the length of the fracture, (Odling 1991). Length of fracture is its longest domain. For representing fracture in three dimension, length and orientation (commonly two angles are adequate) are two important characteristics. A third important characteristic, the location of fractures completes the modelling stages for generating fracture networks. So, three-dimensional modelling follows the same procedure as two-dimensional modelling.

Since actual shape of fractures is difficult to know, it is assumed that fractures are either circular, ellipse or polygon which is easier for calculation and size of individual fractures affects connectivity of fracture network and for that polygon shape is suitable for representing connectivity between fractures. Geometric properties like length, orientation are assigned on the basis of statistical distribution derived from measured data from bore hole logging, satellite image, etc. fractures are randomly located in domain and properties such as density, aperture and orientation are assigned random values. After modeling of fracture network, numerical techniques such as finite element method or finite difference method are applied to calculate flow through fracture network. Hence, for fluid flow through fracture network, DFN model is best suited, which provide a mean for modeling complex fracture / matrix interactions on smaller and larger scale as compared to other known model.

Advantages of DFN modeling

Here, fractures are modelled as discrete fractures rather than group of orthogonally connected fractures inside matrix domain. As in other models, it is assumed that all fractures are well connected to each other but in real environment it might not be so and hence connectivity of fractures plays a vital part in fluid flow and in DFN modeling, it has been given due importance where unconnected fractures are removed and only those fractures that contribute to flow are given importance. DFN modelling is suitable for fractured rocks where rock matrix contributes very less to fluid flow and fractures in rock mass contributes more to fluid flow. Development of discrete feature concept model is very essence of DFN model. DFN model presents three dimensional presentation of fractures and also focus on the flow barriers such as faults and argillaceous layers which hinders flow pathway.

CHAPTER 3: STUDY AREA

Holland et al. (2009a) used FraNEP software for evaluating fracture characteristics of a fractured rock domain in Oman mountains. This study area is located in Jabal Akhtar in Oman mountains. Our study area is represented by lots of faults, veins, fractures of different sizes which is clearly visual in the form of surface outcrops. Below figure shows our study area which is represented as *mark in Oman mountain.

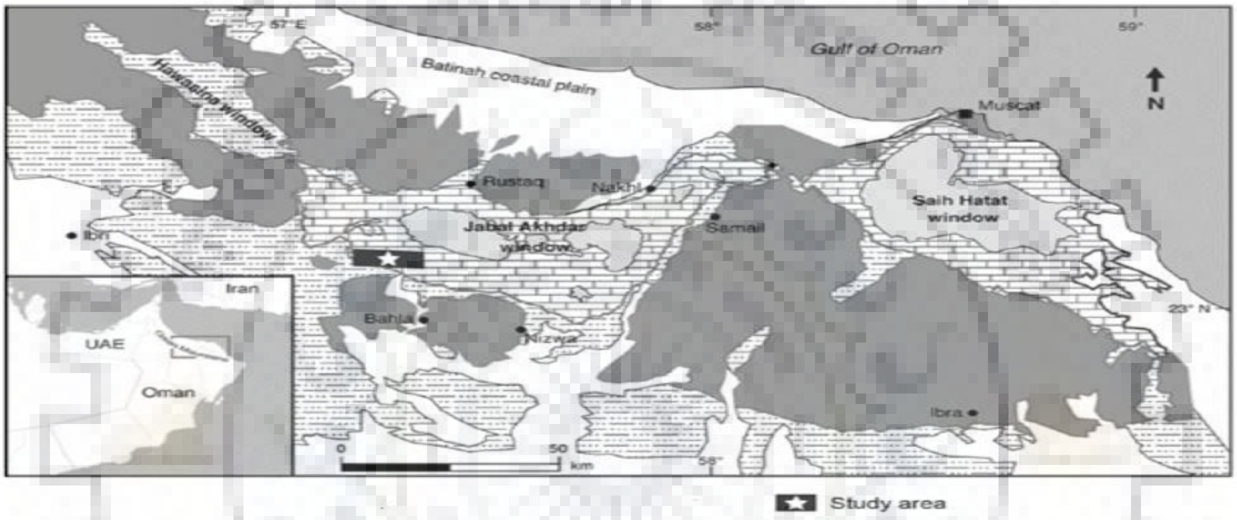


Figure 3.1: Topography of Oman mountain and marked location of study area (marked as star *)

The available input data consists of a polyline shape file, which contains approximately157,000lineaments identified by manual interpretation of a Quickbird satellite image (Holland etal.,2009b).The study area investigated here is a small part of this shape file and contains a total of 1236 lineaments. These lineaments correspond to veins, fractures and joints measured from an outcrop surface. The exposed rocks are mainly Mesozoic limestone's with interbedded shales and marly layers, which were deposited on the southern Neothetyan continental margin from late Jurassic to upper Cretaceous times (Glennie etal.,1973; Bretonetal.,2004). Bretonetal.,2004). Uplift and exhumation of the autochthonous carbonates and the formation of the Jabal Akhdar tectonic window is related to the development of the Makran subduction zone during the Tertiary and still ongoing (Bretonetal.,2004). The complex geological history of the rocks is reflected by numerous sets of discontinuities, including faults of different sizes, fractures, veins, bedding parallel slip surfaces and joints (e.g. Hilgers et al.,2006).

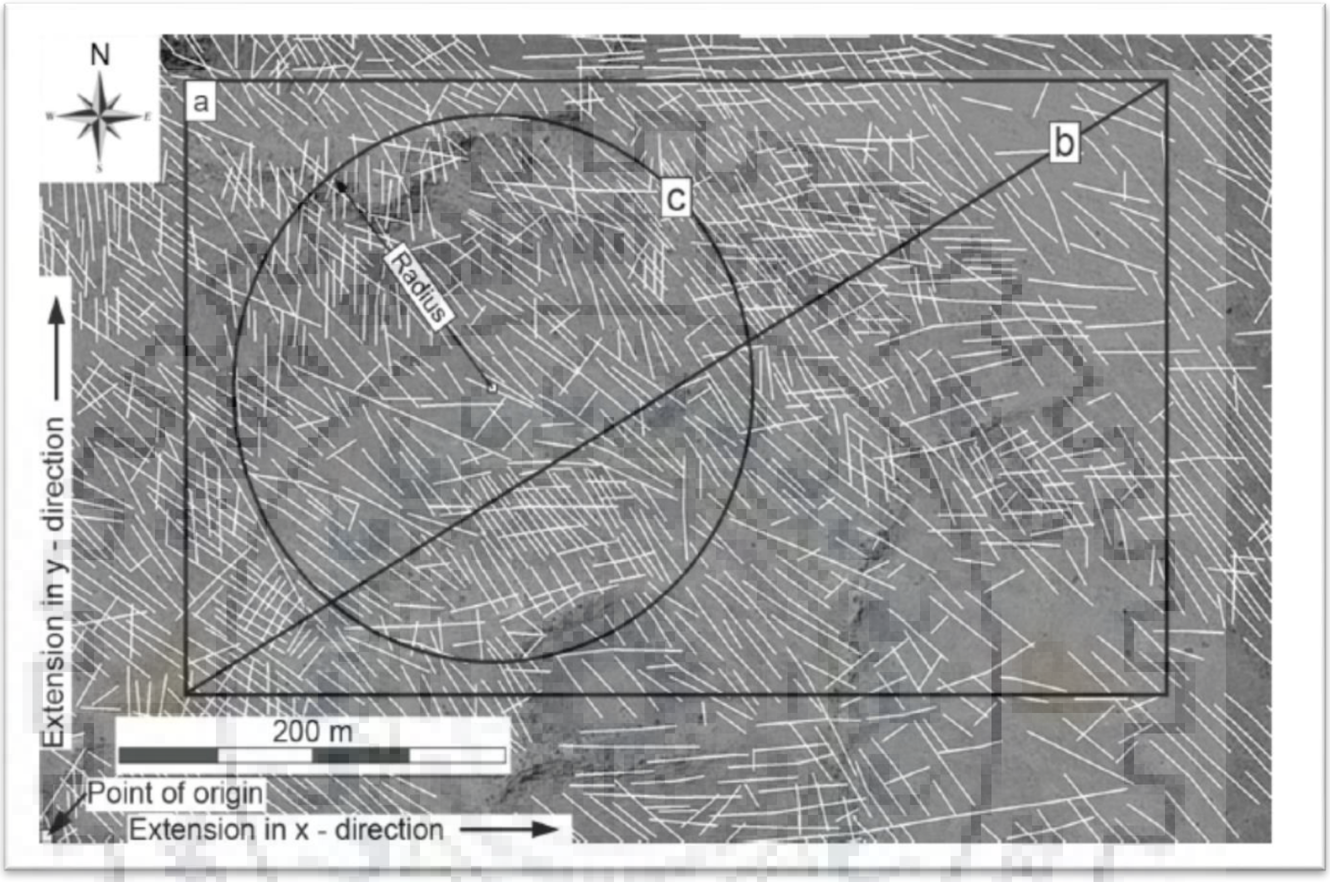


Figure 3.2: Trace line map of study area at Jabal Akhtar dome in Oman mountain with grey lines as lineaments

In figure 3.2, sampling window area is represented as a while scanline and circular sampling locations are marked as b and c. Bottom left corner is taken as origin and extension in X direction and Y direction is taken as 650m and 405m respectively. This trace line map is generated as output from Quickbird satellite image. Trace line has been assigned coordinates which is used as input by FraNEP to study fracture characteristics. Our study area contains approximately 1236 lineaments which is manually interpreted from Quickbird satellite image. All these lineaments are represented by UTS (universal transverse Mercator) coordinate which will be further utilized by FraNEP software.

Chapter 4: Methodology

In this chapter, methodology used in modeling flow through fractures rocks has been described in detail. Calculation of fracture characteristics such as fractures minimum and maximum length, fracture orientation and density are obtained using FraNEP and theory behind it is presented in second section. Fracture characteristics obtained using FraNEP is used to model fracture network in 2/3 dimension and concept behind simulating fracture network model is presented in third section. Fourth section of this chapter contains method to determine fluid flow pathway. In fifth section method to convert fracture model into pipe model is described and finally in last section, flow simulation at 2/3 dimensional scale is presented in detail. Before describing methodology for calculating fracture characteristics, brief description of study area is presented in first section

4.1 Calculation of fracture characteristics

Data acquisition for DFN modeling requires time and manual measurement from bore hole data or surface outcrops. Recent development in the automatic detection of lineages from satellite images and airborne photographs saves time considerably. Popular programs which are used to calculate fracture characteristics from satellite image data are mentioned below.
LINDENS and SAL, LINDENS provides information on fracture density whereas SAL gives information on fracture spacing and its frequency.

FracSim3D is an application which is used for generating fracture network and it also does histogram analysis along with probability and rose diagrams plotting.

FraNEP which is used here provides comprehensive and complete analysis of fractures giving details such as: 1) Individual fracture length and its strike. 2) Characteristics of fracture network such as fracture density, intensity and its mean length. 3) Censoring and correction tools. A detailed description of FraNEP is mentioned below:

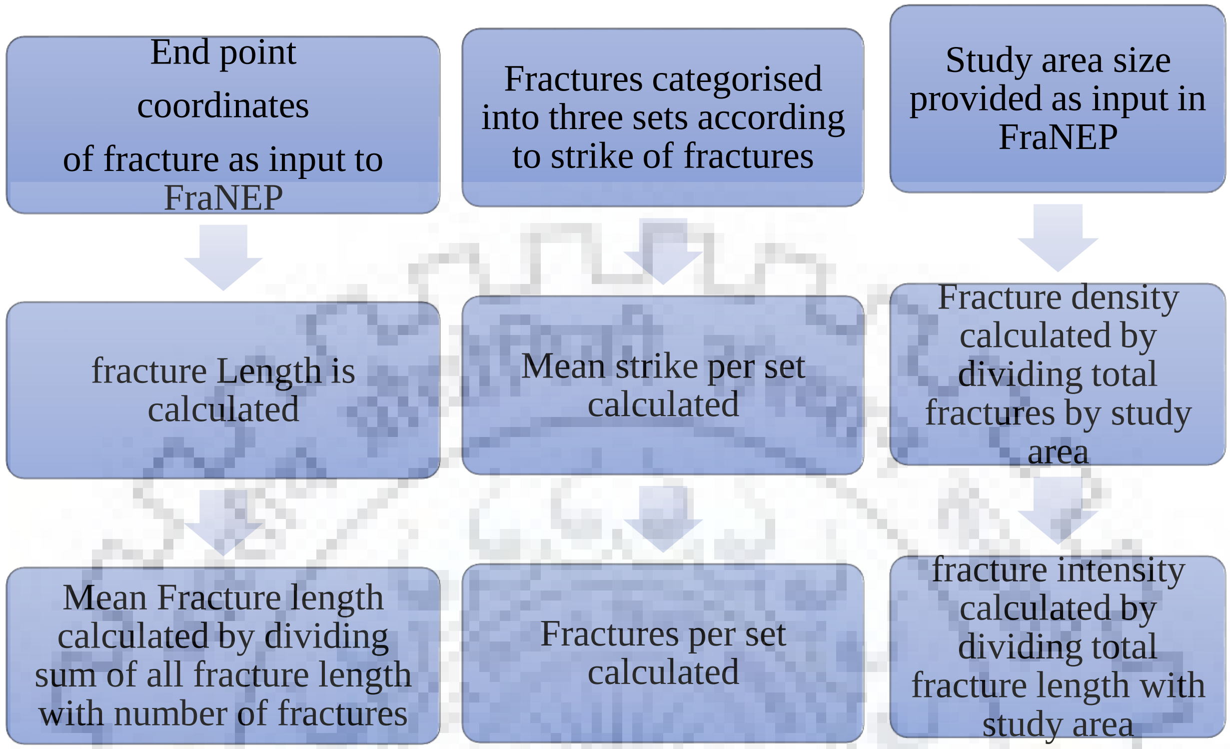
FraNEP Simulator

Geometrical properties of 2D fractures are automatically analyzed by FraNEP based on trace line maps. As input, each fracture is defined by coordinates which are assigned to each fracture through techniques such as automatic genealogy identification via satellite or aerial images. Evaluation of fracture characteristics through trace line map is done by sampling and there are three methods available in FraNEP 1) scanline sampling, 2) window sampling and 3) circular estimator. These methods of sampling can be applied throughout study area or a part of study domain as is the requirement. FraNEP provides main network statistics, which includes the length and strike of each fracture, includes information on fracture density, intensity, estimation for average length and length distribution, and the number of censored fractures.

The strike of fractures can be plotted on the basis of their cumulative number or length of their fracture. Length distribution of fracture is either done automatically, or by selecting one of the three distribution functions namely 1) power law function, 2) lognormal 3) exponential function. Existing software often uses histogram and probability density plot to describe the distribution of length of the fracture. In this simulator, cumulative distribution function is used to determine the best fit, to avoid problems related to binning. The simulator was developed using Visual Basic for applications in Microsoft Excel and combines features present in existing software and characterization techniques like 1) Scanline sampling, 2) window sampling or 3) circular estimator. In addition, instead of the possibility of using density functions, FraNEP avoids binning problems by using cumulative distributions. FraNEP fracture is a time-efficient tool for characterization of network parameters, such as density, intensity and average length.

Therefore, FraNEP is used in this study to analyze trace line map obtained from a satellite image of Jabal Akhtar dome in Oman mountains. Figure 3.3 schematic methodology to evaluate fracture characteristics using FraNEP is given. In step 1, results that are obtained are verified using sampling methods that are given in step II. Among different sampling method, Window sampling method is used to sampled fracture network as results obtained through these sampling is similar to results obtained from step 1.

Step 1: Fracture characterization



Step 2: Fracture Sampling

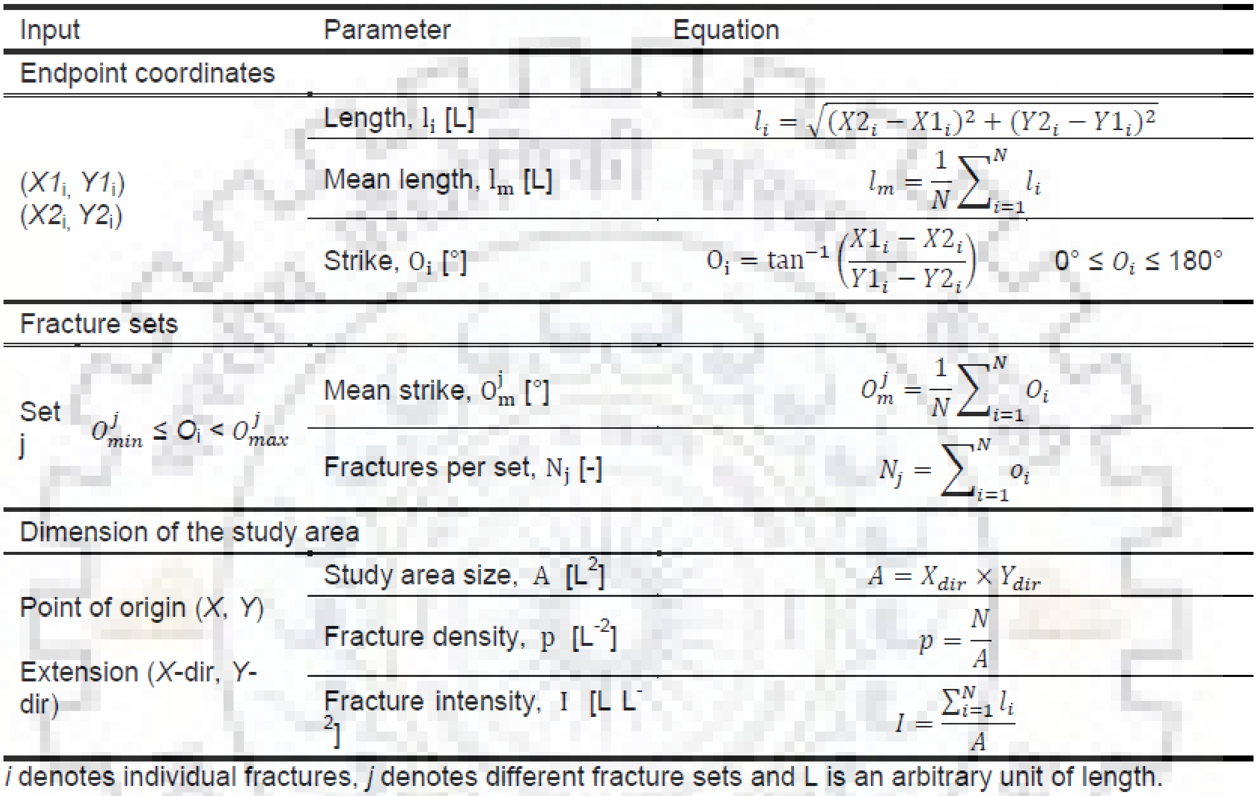
Figure 4.1: Step by step method of evaluation of fracture character through FraNEP

Input data: The following information is required as program input: 1) the endpoint coordinates of each fracture, 2) the number of fracture sets, along with their strike spread (minimum and maximum values) and 3) dimension of study area. The endpoint coordinates (X1, Y1) and (X2, Y2) are imported as points. The length and strike of each fracture is calculated automatically using these two points. A division of this fracture length by the total number of fractures, gives the first estimate of the average fracture length (Table 5). After defining different fracture sets, mean strikes and fractures for each set is calculated (Table 3). The input data can be considered as a single set with strike varying from 0 to 180 degrees in case definition of fracture set is unclear. Size of study area is defined by the coordinates. Expansion in X- and Y-direction, area size, fracture density and fracture intensity are calculated to define the study area (Table 4). A definition of the study area is not required and it can be left, if the size of the study area is unknown, or if data is missing from parts of the area, for example due to erosion, vegetation cover or surface change. The initial results calculated for fracture, length, density and intensity should always be treated with caution. FraNEP includes the possibility of trace-line map preparation from imported fractures UTS coordinates.

Fracture Sampling: Three sampling methods can be applied to evaluate the characteristics of fracture networks: (1) scanline sampling, (2) window sampling and (3) circular estimator. A scanline is defined by the coordinates of its start- and ending points. For the application of window sampling and circular estimator methods, the sample areas are chosen by defining the original point (bottom left Corner) and extension of area in X- and Y directions (Fig.3.2). The fracture crossing a boundary of the selected sample area is considered to be a censored and the intersection point is used to calculate the length of the censored fracture. The Circular Scanline used by circular estimator method is defined by their centers and radius. The centers of circular scanlines are defined by their X- and Y-coordinates and can be kept manually or randomly.

The distance between the boundaries of a sample area and the centers is to equal the smallest constant value of radius plus 0.1 to avoid interaction between the scans and boundaries. The sample area and / or scanline can be placed anywhere within the study area. Although we apply each sample method only once in the example study area, but simultaneously it is also possible to apply 200 sampled areas / lines simultaneously. The fracture network characteristics evaluated by the application of the window and scanline sampling methods are summarized in an extra worksheet for each analysis.

Table 1: Governing Equations on which fracture character is calculated by FraNEP



Input	Parameter	Equation
Endpoint coordinates		
$(X1_i, Y1_i)$ $(X2_i, Y2_i)$	Length, l_i [L]	$l_i = \sqrt{(X2_i - X1_i)^2 + (Y2_i - Y1_i)^2}$
	Mean length, l_m [L]	$l_m = \frac{1}{N}\sum_{i=1}^{N} l_i$
	Strike, O_i [°]	$O_i = \tan^{-1}\left(\frac{X1_i - X2_i}{Y1_i - Y2_i}\right)$ $0° \leq O_i \leq 180°$
Fracture sets		
Set j $O^j_{min} \leq O_i < O^j_{max}$	Mean strike, O^j_m [°]	$O^j_m = \frac{1}{N}\sum_{i=1}^{N} O_i$
	Fractures per set, N_j [-]	$N_j = \sum_{i=1}^{N} o_i$
Dimension of the study area		
Point of origin (*X*, *Y*) Extension (*X*-dir, *Y*-dir)	Study area size, A [L^2]	$A = X_{dir} \times Y_{dir}$
	Fracture density, p [L^{-2}]	$p = \frac{N}{A}$
	Fracture intensity, I [$L\ L^{-2}$]	$I = \frac{\sum_{i=1}^{N} l_i}{A}$

i denotes individual fractures, *j* denotes different fracture sets and L is an arbitrary unit of length.

Analysis of fracture length

The length of fracture distribution is evaluated using cumulative distribution function of below mentioned equation. Equations to calculate length of the fracture are: a) the power law equation (eq. 1), b) lognormal (eq. 2) and c) exponential (eq. 3). Power law equation is given as:

$$f(l) = 1 - \left(\frac{l}{l_0}\right)^{-E} \tag{1}$$

Where l is the fracture length, l_0 is the shortest observed fracture length and E is the power-law exponent. The lognormal distribution is also commonly used to describe fracture lengths. The cumulative distribution function of a lognormal distribution is:

$$f(l) = 0.5 + 0.5Erf\left(\frac{Ln(l)-\mu}{\sqrt{2\sigma^2}}\right) \tag{2}$$

Where μ and σ are the mean and the standard deviation of the natural logarithm of l. The cumulative distribution function of an exponential distribution function is:

$$F(x) = \begin{cases} 1 - e^{-\lambda x} & ,x \geq 0 \\ 0 & ,x < 0 \end{cases}$$

where

$$\lambda = \text{Rate Parameter} \tag{3}$$

we can use any of above distributions to the fracture length data or allow FraNEP to determine the best-fitting length distribution automatically. The accuracy of the best fit is indicated by a) root mean squared error (RMSE) (eq. 4), b) sum of squared errors (SSE) (eq. 5) c) maximum squared error (MSE) (eq. 6). The RMSE is given by:

$$\text{RMSE} = \sqrt{\sum_{i=1}^{N} (P_i - O_i)^2 / N} \tag{4}$$

Where n is the total number of measurements, P is the predicted/calculated value and O is the observed/measured value. The RMSE is commonly used to compare the best fits of different data. The SSE is a simplification of the RMSE and is given by:

$$\text{SSE} = \sum_{i=1}^{N} (P_i - O_i)^2 \tag{5}$$

For the automatic evaluation of the best fit the SSE is used, which is valid since the three distribution functions (Eqs. 2-4) are fitted to the same data. MSE equation is mentioned below:

$$\mathrm{MSE} = (P_i - O_i)^2 \Big|_{i=1}^{N} \tag{6}$$

Cumulative distribution of the fracture lengths measured by application of the window sampling method to the field example at Jabal Akhtar dome in Oman mountains is plotted which shows RMSE value of 0.014.

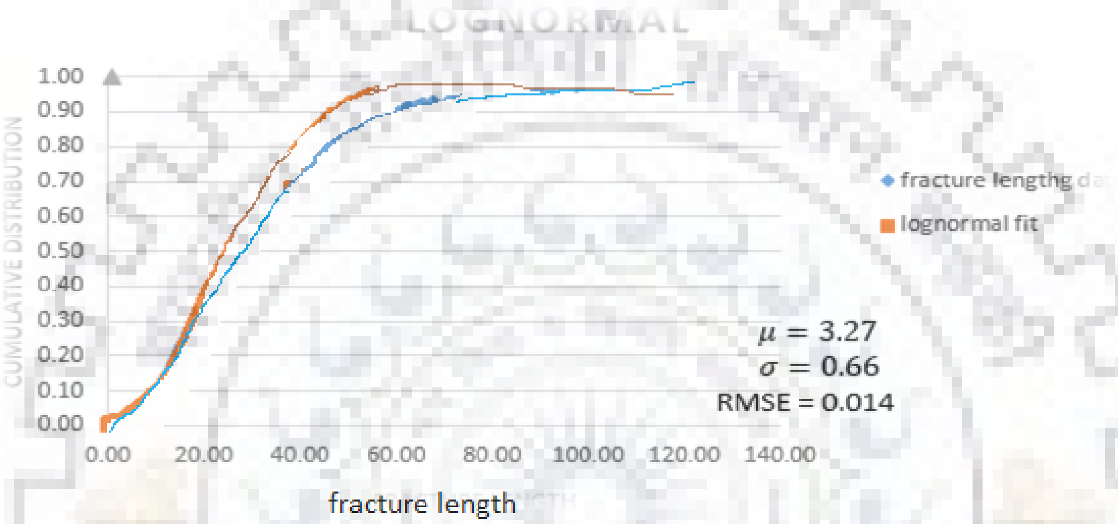


Figure 4.2: graph illustrating the fit of lognormal function with parameters of distribution function.

4.2 Fracture Network Modeling

Important definitions and terminology used in Fracture network modelling are described below.

Point - A fracture can be represented by a point (i.e., its geometric center, see the next part), thus its position is only in coordinates (x, y, z). Similarly, fracture clusters, fracture hyper clusters and fracture networks may also be located from one point. From the definition, the location of a point can have arbitrary number of dimensions while commonly a pair of two (i.e. p = (x, y)), for fractures in two dimensional (fracture traces) and three (i.e. p = (x, y, z)), for fractures in three-dimensional space) real numeric values is used (Haining 2004).

Center of Geometry - The most representative location point for a geometrical object (O) is its Centre of Geometry (CoG, or geometrical center; Murayama and Thapa 2011). For geometrically complex shapes CoG is preferred over the commonly used center of mass (CoM, Weltner et al. 2009). Assuming three-dimensional fractures as flat polygon with evenly distributed mass the CoM can easily be found by averaging the coordinates of their vertices (i.e., boundary points). However, for fractures with spatially-uneven located vertices, CoM will be closer to the denser areas (Figure 12). The CoG incorporates the distance between two adjacent vertices, i.e., edges. Hence every fracture, whether two- or three-dimensional, is an object that can be conveniently located by its CoG.

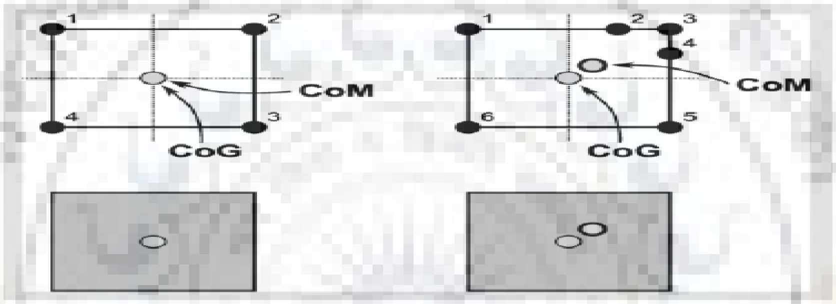


Figure 4.3: CoG vs CoM, CoG is more resistant against more number of points and so more suitable

Line - A line is the simplest one-dimensional object and is fully specified by its finishing points, P_1 and P_2 (Weltner et al., 2009). It can also be specified by a point and angle (α). The term line means a finite line i.e. a segment.

$$\mathbf{L} = \{\mathbf{P}_1, \mathbf{P}_2\} \quad \text{or} \quad \mathbf{L} = \{\mathbf{P}_1, \alpha, l\}$$

An intersection of a fracture with an exposed surface, such as an outcrop, appears on the surface as a line, usually called the fracture trace line (Odling 1992) or simply a trace and trace can be treated as a straight line. The intersection of two fractures in three dimensions is a line or a point, depending on the size of the fracture and their relative arrangement in a three-dimensional space.

Polygon - A quadrilateral, which is the simplest four-vertical convex polygon, is used to model three-dimensional fracture (Blocher et al., 2010). Any quadratic representation of fracture can be estimated by an ellipse. The elliptical representation of fracture is commonly used, primarily due to its simplicity in the calculation. But this simplification has significant errors in the approximation of fracture intersections in particular. In the light of the COG concept, it can be generalized that there are very rare cases where the COG of an ellipse matches the COG of the original polygon fracture. The area and perimeter of a modelled ellipse would be significantly different than of the fracture. These errors are more problematic when dealing with fracture network modelled by ellipses in order to analysis the connectivity, intersection and topology.

In addition, any statistic inferred from elliptical approximations of fractures is heavily biased. On the other hand, polygonal modelling avoids all the above mentioned problems as it matches any complexity in the shape of fractures either perfectly or with a negligible approximation. Polygonal representation represents high-effectiveness in modeling, high performance computation, high accuracy in fitting, high flexibility in dealing with complexity in the size of the fracture and high realism in fracture and model of fracture network.

Mechanism for fracture generation in DFN

Fracture locations are represented by points - the center of 2D shapes or the center of 3D shapes. Stochastic modeling of the fracture is based on a discrete fracture network concept, in which fractures are produced in a stochastic way according to an inherent underlying mechanism. Following points describes process of fracture network modeling:

- Fracture locations are generated based on either a Poisson (homogeneous) point process or an inhomogeneous point process (Fig. 3.5).
- Fracture orientations are derived by means of Fisher or Von-Misses distribution functions (Fig.3.8).
- Fracture shapes (lines in 2D and polygon in 3D) are defined and fracture sizes are drawn from its distributions, either exponential or lognormal.
- Other features can be added as required such as aperture, transmissivity and surface roughness as per requirement at site.

<u>Fracture location:</u> Point location of fracture is the most fundamental feature in DFN and it is initially defined through distribution functions (Kendall 2003). Points can be independently distributed in study domain or Points can be uniformly distributed or an alternative is clustering scheme in which the points are distributed unevenly on the study domain(Fig:3.5). These three

forms cover most patterns because any pattern other than these three can be made by combining three forms. If a pattern is static (irreversible) in space, then it is called homogeneous otherwise inhomogeneous (Illien et al. 2008). An inhomogeneous pattern is a point process in which there is a variable density based on location in the study area. The density function (Xu et al. 2003a) can be simple or complex, linear or higher order. For example, a multi-Gaussian density map (Xu et al. 2003b) can be used to generate clustered point patterns (Fig.3.6).

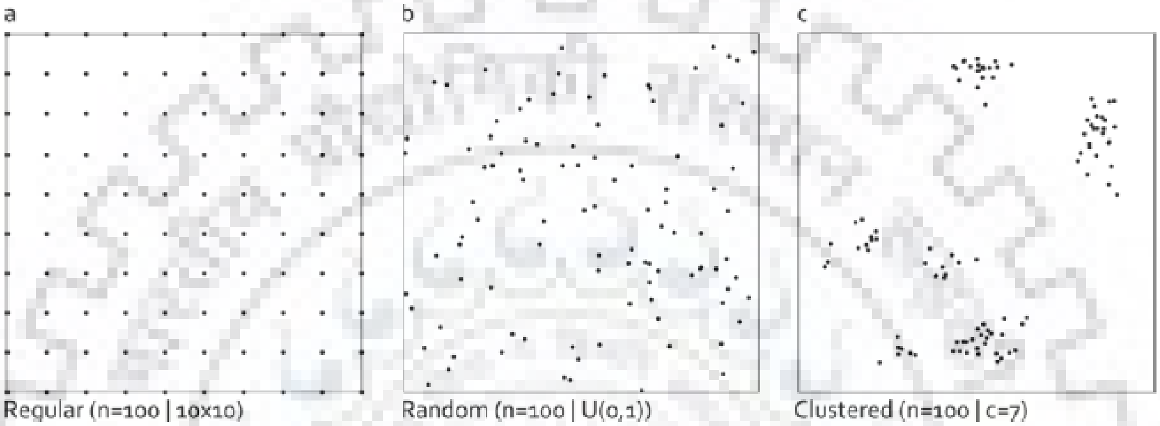


Figure 4.4: Different methods by which location of a point can be distributed in study area

Random patterns can be simulated using any functions like uniform, Gaussian, Poisson, exponential distribution functions. Of these, the homogeneous Poison pattern is statistically known as a standard example point process that meets the criteria of complete spatial randomization (Diggle 2003).

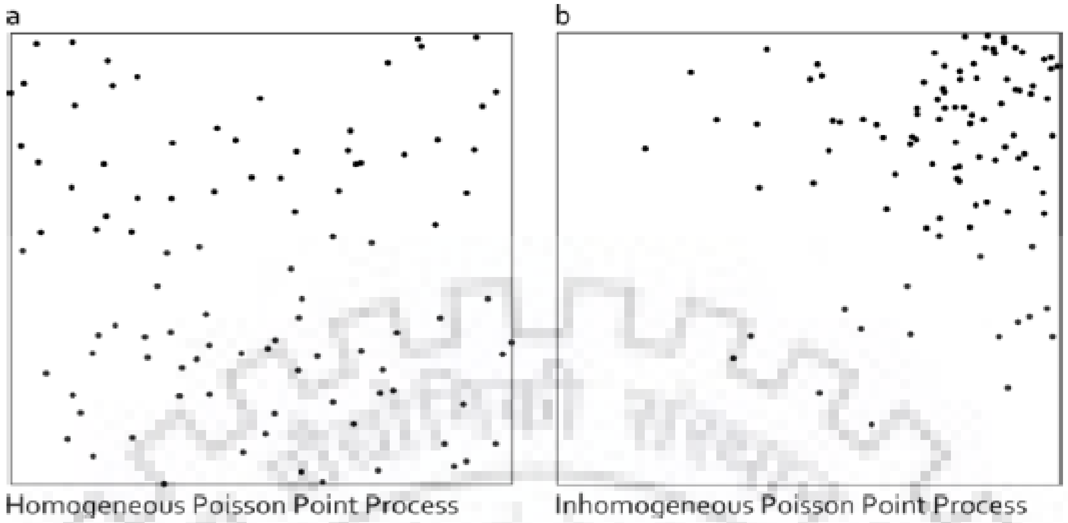


Figure 4.5: Homogeneous and Inhomogeneous point process for fracture location generation

In a similar way, location points can be generated for three-dimensional fracture networks as shown in Figure 14 (Illian et al. 2008).

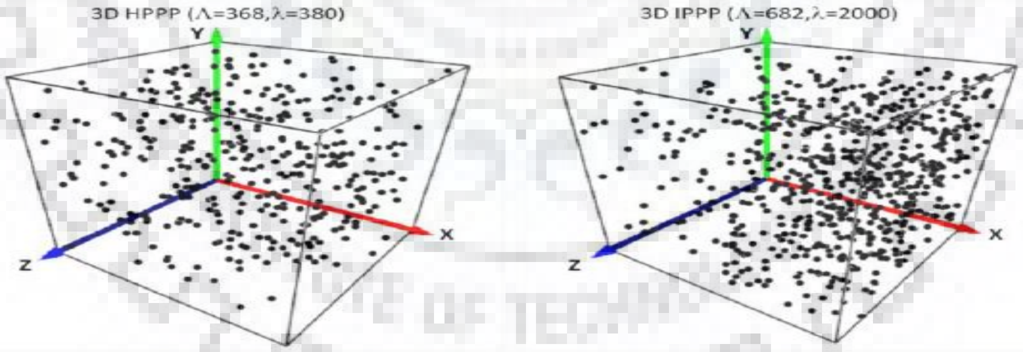


Figure 4.6: Two different sets of poison point process for three dimensional fracture

Fracture Orientation: Common distributions function used for simulating fracture orientation in rock mass are von Mises (or spherical normal) for two dimensions and Fisher distribution for three dimensions and (Fadakar- et al. 2011). Figure 3.8 shows fracture network with oriented, semi-oriented and Omni-directional orientations. The tilt of all three sets were generated from the Von Mises distribution by setting dispersion factor κ(kappa) equals to 1000, 10 and 0 for sub-figures a, b and c, respectively. The mean orientation for the three simulations is zero (horizontal). Any degree of orientation complexity can be achieved by combining several fracture orientations generated from von-Mises distributions.

Figure 4.7: Different ways by which fracture orientation can be modeled

Fracture Length: Fracture length can be modeled by probability distributions, including uniform, Gaussian, power-law, exponential and log-normal distribution (odling;1992) Power-law distribution is widely used for simulating length in DFN. Power-law distribution when used in simulation, gives very less number of larger fracture length and greater number of fracture length with smaller and medium length which matches the real fracture environment in field where longer fractures are less.

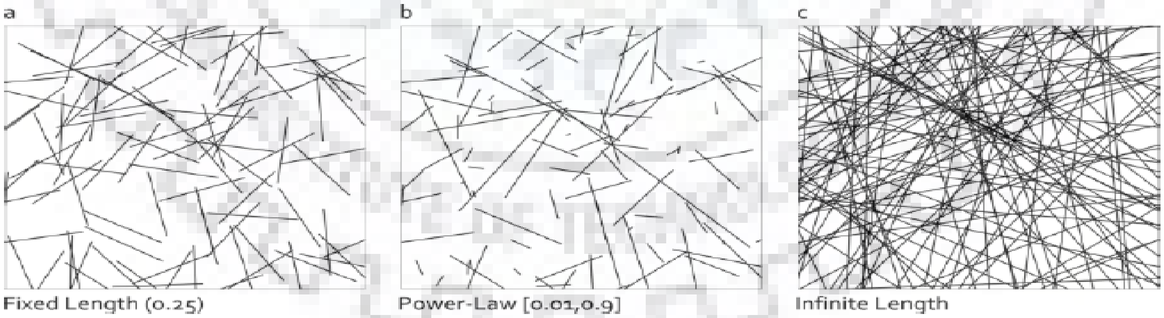


Figure 4.8: Stochastic distribution function used for Fracture length calculation

From Fig. 3.9, we can observe that DFN modelling can simulate any complex fracture network model that satisfy almost any natural situation whilst keeping the modelling procedure straightforward and practical.

4.3 Flow pathway in fracture network model

After fracture network model is prepared using statistical distributions, next step is determining fluid flow pathway in fracture network. To determine flow pathway, connectivity of fractures need to determined. Below section gives methodology on how to determine fracture connectivity:

Fracture connectivity

Fracture connectivity refers to interconnection of individual fractures to form coherent network. It is sensitive to network geometry and fracture characteristics such as length, size distributions, orientation, density and aperture of individual fractures. Connectivity also depends on the spatial distribution and interaction of different fracture sets to form a continuous network (Odling et al., 1999). For any fracture network that is not isolated, interconnection between fractures produces fracture cluster (sub-network or sub-network of sub-fracture). Connectivity of a fracture network is internally associated with fracture intersections and therefore fracture clusters. Connectivity of fractures effects fluid pathway in fractured rock and thus proper evaluation of fracture connectivity in fracture network model is important for flow simulation. Following factors affect fracture connectivity.

1) An increasing number of fractures of the same set are added to the system resulting in an increase in fracture density.

2) The length of the fractures increases.

3) The orientation of fractures in a set exhibits a higher degree of dispersion.

4) Fractures of multiple sets are added to the system.

In fracture network, Connectivity of fractures is evaluated using Connectivity Index(CI) function.

Connectivity Index(CI): The CI function describes the relationship between two points in space i.e. if two points are connected, CI value is 1 otherwise it is 0. CI is the probability that two arbitrary points within the region are connected and so CI is independent of local scale of the region. Monte Carlo simulation is used to evaluate the connectivity index and to assess the influence on connectivity of different fracture network models (Xu et al., 2006).

Fracture Intersection analysis: It helps in determination of intersections between lines in Two-dimensional and Three dimensional fracture network. It forms first phase in the connectivity analysis of the fracture network between polygons. Analysis of fracture intersection (fracture-connection) in the fracture network is an important step in evaluating fluid flow pathway.

Fracture clusters: Fracture clusters are formed by the group of interconnected fractures. There are at least two fractures in a cluster. The existence of groups in a fracture network can be associated with the complexity of fractures interconnection in fracture network (Hudson 1985). After intersection analysis, fractures are clustered and then the clustering information is used to determine the connectivity of the fracture network. This is very useful for rapid evaluation of connectivity between newly added fracture or fracture sets (e.g., support edges) and existing fracture network.

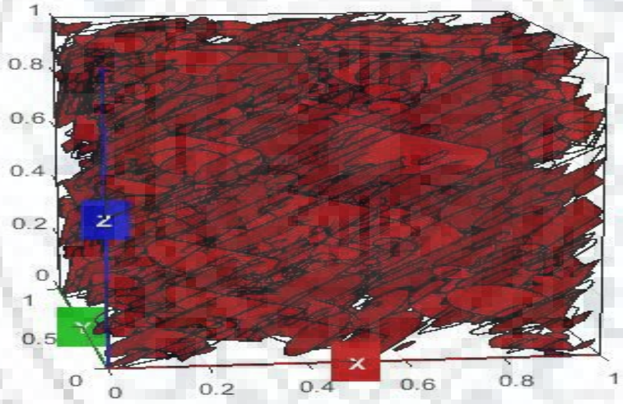
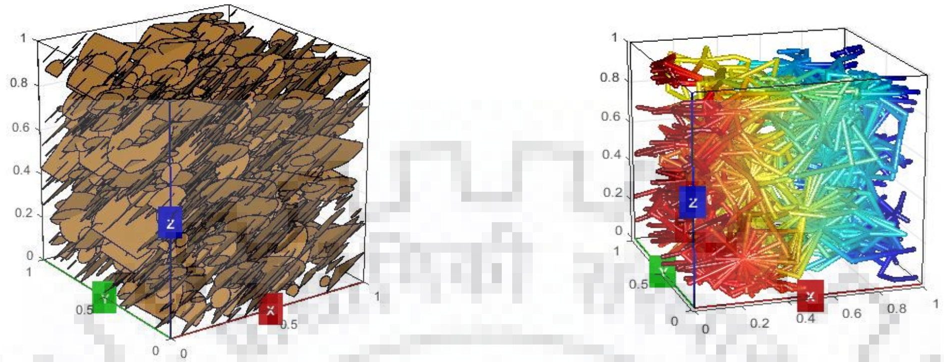


Figure 4.9: Three dimensional view of clustered fracture network model where dark red and light red are two connected fracture sets

4.4 Fracture Network as Pipe Model

After determining fracture connectivity, next step is flow simulation and finite element method is widely used method. Figure 3.11(a) gives an indication of complexity of Three dimensional fracture network that have to be meshed in preparation for simulation by finite element method. Hence, best way is to simulate flow using pipe model (Xu et al. 2013a). Below two methods for creating pipe model from fractures in 2/3 dimension is presented which can be further used for flow simulation.



(a) (b)

Figure 4.10: Above image showing conversion of 3D fracture network model where fracture is as polygon shape into 3D pipe model

There are two ways by which pipe model can be built-

Triangulation Method

The first form of pipe model can be established by connecting intersection center points as shown in the following figure.

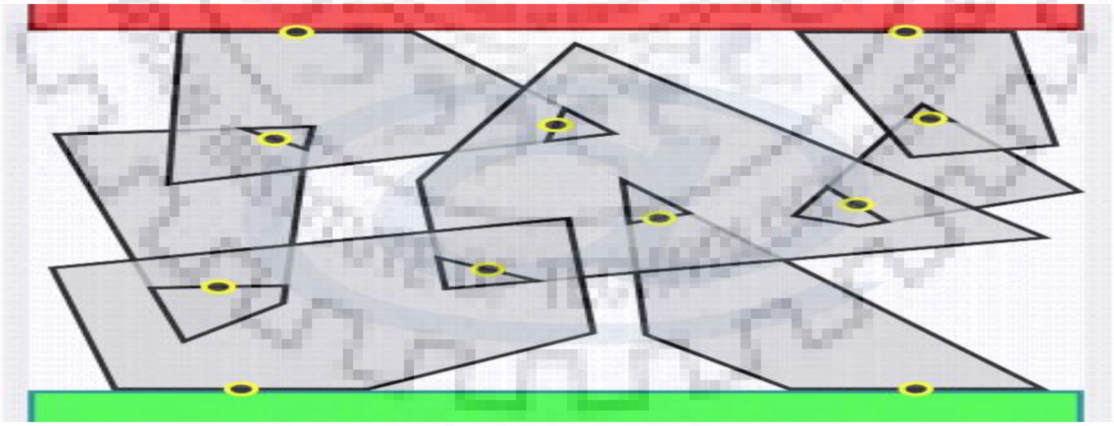


Figure 4.11: polygon shaped fractures with yellow dots showing center of two fractures intersection

Intersection between inlet,outlet and other fractures are included so that a percolating network is built.These networks is used to model subsequent flow.

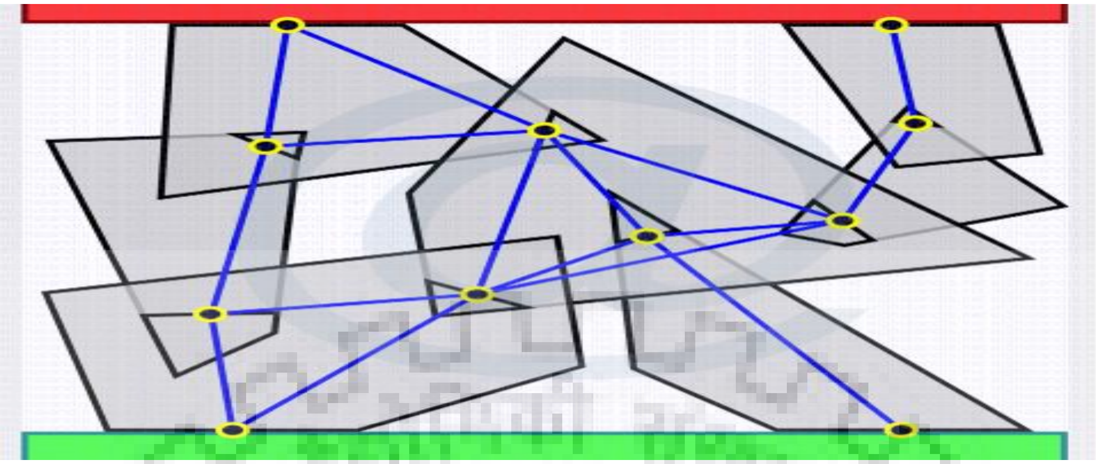


Figure 4.12: Yellow dots representing fracture intersection center are conneted by blue line to form pipe moel and then subsequently used as flow pathway

Polygon Method

In this method,first centroid of fracture is calculated and then it is connected with associated intersection centres. Here,for flow modelling yellow dots are connected.

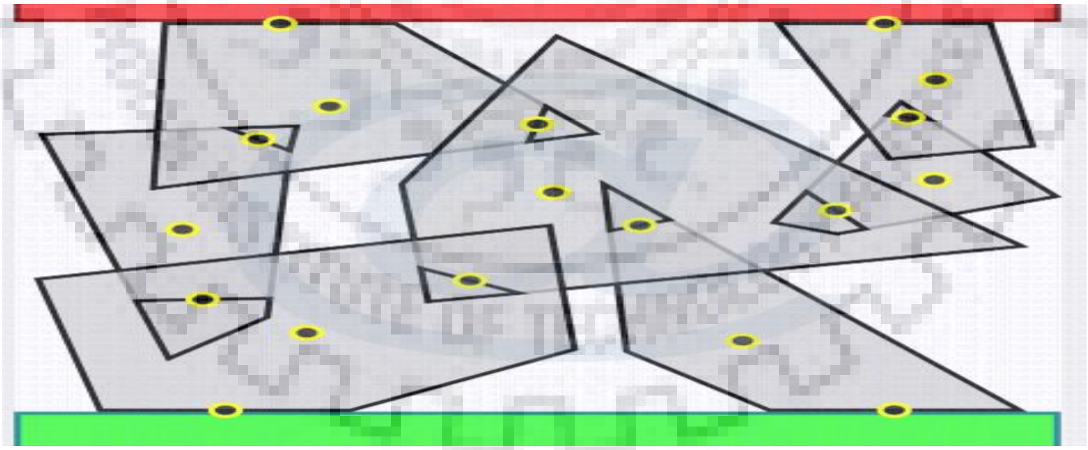


Figure 4.13: Here yellow dots represent center of fractures as well as center of fracture intersection

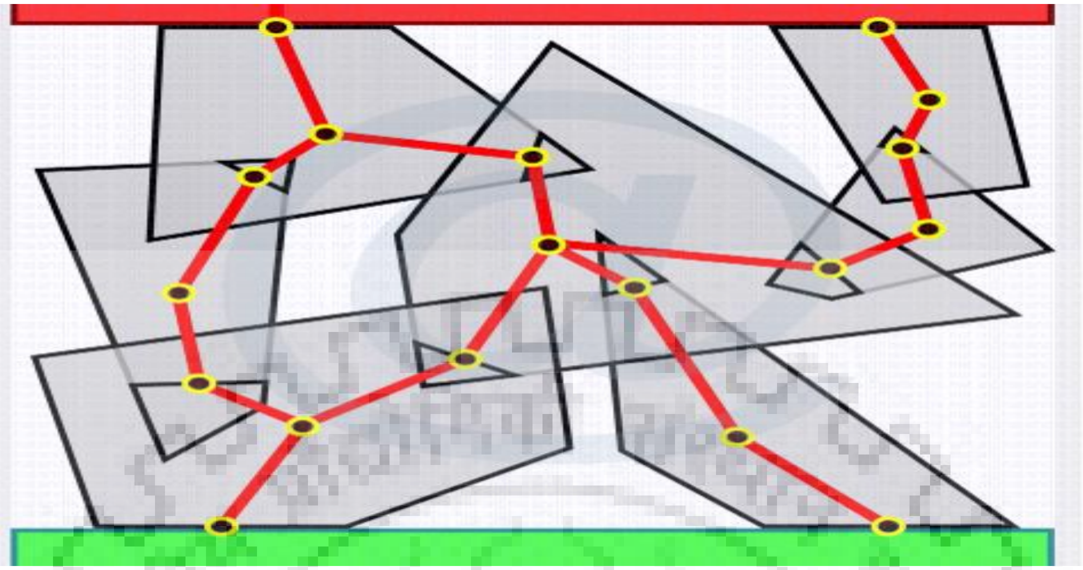


Figure 4.14: : All the yellow dots are connected to represent flow pathway

This method is straightforward, fast and free of complication in terms of efficient implementation. We name this method as *Center method*, hereafter; its full algorithm is as follows.**(i)** Find center of fractures i.e., centers - *cts* **(ii)** Find center of intersection lines - *cxs* **(iii)** Create pipes by connecting any *cts* to *cxs* - *pip* **(iv)** Distribute clustering and other information of fractures to pipes - *pip*

The center of the fracture can be easily found by calculating the average value of the coordinates of all its corners, or by calculating its nucleus more firmly. Note that if the intersection was a point, then as a generalization, we consider it as a line with zero length. On step (iv), we transmit essential information inherited from the fracture such as fracture clustering label and aperture in the generated pipe. These properties will be used in the solution phase.

4.5 Flow Simulation in Multidimensional Fracture Network

For flow modeling, representing pipes in the form of nodes and edges is foremost step. preprocessing operation (cleaning function) can help to remove duplicate pipes and those with zero (or very small) lengths. Pipes are modeled as such that its radius defines aperture of fractures and in this study aperture of all fractures is taken as constant. On graph model created, those edges and nodes that are related to inlet and outlet polygons (boundary conditions) are marked accordingly, while all other nodes are marked as unknown in the system. According to the problem of interest, e.g., pressure heads, the inlet and outlet nodes are assigned the corresponding boundary values. A system of linear equations for n (number of inner nodes) unknowns can then be built. Linear solvers, either direct or iterative methods, can then be used to solve pressure distributions for all nodes.

Graph Theory

Working principle of graph theory includes extraction of nodes, edges and their associations (topology). To prepare graph, first step is to extract the backbone of fracture networks which is by itself a key step for fluid flow modeling in the network. Generating backbone from two- and three dimensional fracture networks follows the below mentioned algorithm.

```
Bls = BreakLinesX D (lines);     %2D FNM
Bbn =Backbone(bls);               %backbone
Pip = Pipes3D(polys);             %3D FNM
Bbn = Backbone(pip);             % Backbone
```

where lines is fracture network, bls is broken lines in their intersections by means of BreakLinesX2D function, and bbn is the resulting backbone structure.

For three dimensional fracture network (polys), Pipes3D function generates pipe model from which the backbone structure is extracted. A pipe for a fracture can be made between its centroid and its center of intersection with another fracture as explained in methodology. Generic function BackboneToGraph transforms backbone structure into graph structure in which nodes, edges and the associated topology provide an exceptional opportunity to investigate complex properties of fracture networks in a very straightforward manner. An example for this is the fluid flow modeling (Fadakar-A et al., 2013b) by application of finite difference methods which can be elegantly done based on the graph inlet, inner and outlet nodes and some efficient functions such as neighboring.

Flow modelling

In this study, fluid flow modeling is based on concept of Finite Difference Method. All income and outgoing flow to and from a node must fully match, that is, mass conservation is used in fracture network. Under Darcy's law for laminar flow of incompressible fluid, the following simplified equations are used to determine the pressure head distribution for every node in the graph of any 2/3 dimensional fracture networks (Priest, 1993).

$$H_j = \frac{\sum_{i=1}^{n} C_{ij}H_i}{\sum_{i=1}^{n} C_{ij}}, \qquad n \in [2, 3, 4]; \qquad\qquad C_{ij} = \frac{ga^3b}{12\nu L}$$

where C_{ij} is the conductance between nodes i and j calculated based on g, the gravity acceleration (9.8 m/s2), a, the aperture (m), b, the third dimension of fracture (here 1 for two-dimensional case), v, the kinematic viscosity (10−6 m2/s for water), and L, the length (m). Hj is the head pressure at node practically, nodes are categorized into three types: inlet, inner and outlet nodes. The flow (here pressure head, for example) starts from the inlet nodes and distributes through the inner nodes to reach the outlet nodes. Based on graph structure, for every inner node the neighboring nodes are found for which the matrix of unknowns is constructed following the above equations. As shown, the values inserted in the matrix incorporate conductance factor (Priest, 1993) which itself is calculated based on the neighboring edges' properties as explained. When the matrix system (AX=B) is fully prepared, a simple linear algebra technique helps to find a solution (X=A/B). The resulting solution includes pressure head value for all inner nodes.

The following functions from ADFNE help to achieve the mentioned flow solution.

G = BackboneToGraph(bbn);
G = SolveFlow (g, inlet, outlet);
where bbn is backbone, G is the resulting graph." Solve" Flow function accepts the graph G, inlet and outlet pressure heads and returns the solution as an updated graph.

Chapter 5: Results and Discussion

A list of input data set along with the obtained fracture parameters of the Jabal Akhtar dome in Oman mountains is listed in Table 1. Only one fracture is taken as an example for the calculation of fracture length and its strike as the findings of all 1236 fractures can't be plotted. All fractures are categorized into three different sets according to their strikes as shown in Table 2 and number of fractures per set is calculated and shown in Table 2. In Table 3, study area size and fracture network characteristics like fracture density and fracture intensity are shown. When modeling fracture network in 2D, each set of fractures is modeled individually and then all three sets are combined into a single fracture network model. Section 4.1 contains fracture network model of Jabal Akhtar dome in Oman mountains in 2/3 dimension. Connectivity of fractures are modeled and result are presented in section 4.2 whereas Flow simulation result for 2/3 dimensional fracture network is presented in section 4.3.

Table 2: Input and result calculation for single fracture at Jabal Akhtar dome

INPUT **(**Endpoint coordinates)*	**PARAMETERS**	**RESULT**
$X_1 = 517830$, $Y_1 = 2564405$	Length	66.7m
$X_2 = 517777$, $Y_2 = 2564445$	Mean Length	31.3m
	Mean Strike	127.2^0

*** = UTM coordinates**

Table 3: categorization of all fractures into different sets and fractures per set calculation

FRACTURE SET	**STRIKE (Degree)**	**MEAN STRIKE (Degree)**	**NUMBER OF FRACTURES PER SET**
Set 1	10^0<O<100^0	68.9^0	294
Set 2	100^0<O<155^0	133.4^0	770
Set3	155^0<O<010^0	178.4^0	172

Note: Total number of fractures in study area at Jabal Akhtar dome is 1236

Table 4: Calculation of fracture network characteristics

Study area size(X,Y)	650m*405m
Fracture Density(m^{-2})	0.005
Fracture Intensity(mm^{-2})	0.15

Table 5: Fracture network characteristics of Jabal Akhtar dome evaluated by three sampling methods

Parameter	window	scanline	Circular
Sampled area(m^2) and for scanline(m)	$2.63*10^5$	583	$2.63*10^5$
Number of fractures	1236	74	
Fracture density(m^{-2})	0.005	*	0.004
Fracture intensity(mm^{-2}) or fracture frequency(scanline) (m^{-1})	0.15	0.13	0.17
Mean Fracture Length(m)	31.3	41.8	42.5

* = Method provides no information

The characteristics of the fracture network obtained with three sampling methods are listed in Table 5. This table shows that the fracture parameters are quite different, in each of three sampling methods. An explanation of this variation in different sampling methods is mentioned in methodology section. For example, the probability of a fracture with a scanline sampling method is proportional to its length and hence number of fractures also increases. Under representation of small fracture makes the difference in the fracture intensity and the average length value obtained through window and scanline sampling methods. For the application of the circular estimator method, it was found that the radius of Circular Scanlines should be at least 45 meters for the current study. For this radius, values of fracture density are similar to those obtained from window sampling method. Fracture network of study domain is modeled in 2/3 dimension and results are presented in next section along with results of Flow simulation

5.1 Generation of fracture lines

Results obtained from FraNEP in form of fracture length, fracture orientation, fracture density and total number of fractures in study domain are used as an input data set for simulating fracture lines using MATLAB coding. Following section includes different function used to create fracture network model, to determine connectivity between fractures and then subsequent flow modeling in Two dimension and Three dimension. Two-dimensional fracture network is simulated here by means of GenFNM2D function:

lines = *GenFNM2D* (*n*, *theta*, *kappa*, *minl*, *maxl*, *rgn*);

where n is the number of fractures, theta is the mean orientation [0 to 2π), kappa is dispersion factor for the orientation (≥ 0), minl is minimum length (> 0) and maxl is maximum length (>*minl*) for fractures, and rgn is the region of study [*x* , *x* , *y* , *y*] *min max min max* by which the simulated fracture network is clipped. The use of minl and maxl helps to avoid generating very short and very long fractures. The length value for each fracture is obtained from negative Exponential (E) distribution.

By executing these function in MATLAB with three sets of fracture strike (Table 2), a 2D fracture network model is created which represents fracture network at Jabal Akhtar dome. Fluid do not flow in all the fractures represented in 2D model and preprocessing operation needs to be done that removes unconnected fractures.

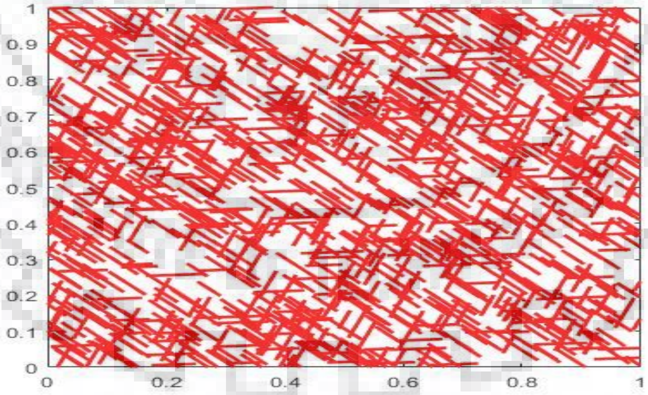


Figure 5.1: Two dimensional fracture model created using MATLAB for our study area in 1m*1m domain

Similarly, three dimensional fracture network can also be modeled using following function:

polys = *GenFNM3D*(*n*, *dip*, *ddip*, *ddir*, *dddir*, *rgn*, *s*);

where n is the number of fractures, dip is the mean dip angle $[0. . \pi/2)$, ddip is variation limit around the dip angle $(0 \leq ddip \leq \pi/4)$, ddir is the mean orientation $[0. . 2\pi)$ and dddir is variation limit around the ddir angle $(0 \leq dddir \leq \pi)$ for fractures, rgn is the region of study [x , x , y , y , z , z] $min\ max\ min\ max\ min\ max$ (a cube) by which the simulated fracture network is clipped and s is the scaling factor to determine maximum size (s=Smax) for generated fracture lengths which follow negative exponential distribution.

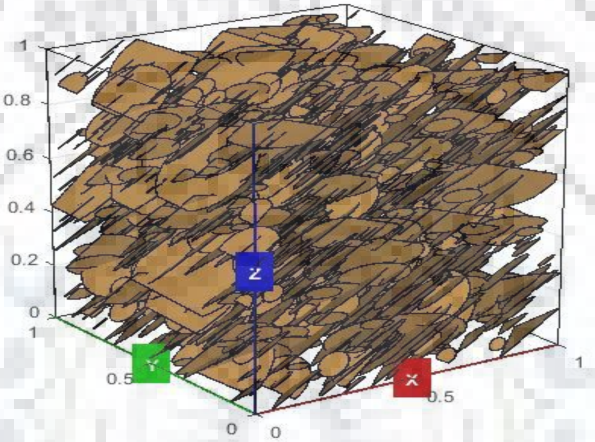


Figure 5.2: Three dimensional model representing fractures in our study area in 1m*1m dimensional space

5.2 Fracture Connectivity Analysis

Connectivity of fractures is key characteristics for variety of application and in this study, it is useful for determining preferential fluid pathway. The complexity of preferential fluid pathways through fractures, spatial distribution pattern of active fracture clusters in the network, are all closely associated with the connectivity properties of fracture network.

To evaluate fracture connectivity, Connectivity Index(CI) function is developed whose detailed methodology is presented in previous chapter. But before using Connectivity Index(CI) function, Fracture intersection analysis and cluster analysis is done on the simulated fracture network model and clustered model obtained is used as input by Connectivity Index (CI) function to create preferential fluid pathway in fracture network.

Fracture Intersection Analysis

In two dimensional fracture networks any two fractures can intersect as a single point while for three dimensional fracture networks, intersection could be a point or line. For, either case intersections are the most important characteristic of fracture networks as they define the connectivity properties of the network which effects fluids flow through fractures as they commute from one to another location (fracture) via intersections between fractures; As discussed in methodology, for evaluating connectivity of fractures, first operation to be performed is intersection analysis which is done using” Intersect” function.

Fracture Cluster Analysis

Information obtained from intersection analysis is used as input to determine Fracture cluster in network. A fracture cluster is defined as group of interconnected fractures where connectivity between fractures can be directly or through interconnected fractures in fracture network. Fracture network is clustered in different groups of interconnected fractures and the one group which connects fracture from one end taken as inlet to other end taken outlet defines fluid pathway in fracture network.

Figure 4.3 represents clustered three dimensional fractures network obtained using “cluster” functions. Here every color of fracture polygons, represent group of interconnected fracture present in our study domain. Among these groups of interconnected fractures, one that connects inlet and outlet is accepted as preferential fluid flow pathway which can be more than one. Next step is determination of fluid pathway for which Connectivity Index (CI) function is used which is described in next section.

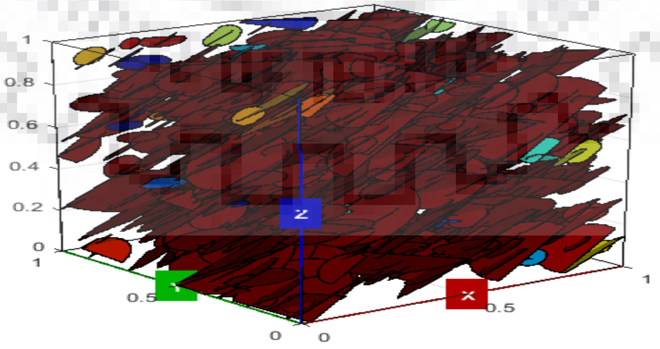


Figure 5.3: Representation of 3D fracture in clusters with deep red polygons showing connected fractures and isolated fractures with light red color.

Connectivity Index

If two fractures are connected directly or through intermediate fractures, its connectivity value is “one” otherwise “zero”, i.e., {1: $f \leftrightarrow f$, 0: $f \nleftrightarrow f$}. In a simulation of several realizations from a fracture network model the number of times that the two portions (sub-regions, supports) of the area of study remain connected via fractures determines the CI probability value between them. Figure 4.4 shows flow pathway in fractured network of Jabal Akhtar dome in Oman mountains. Connectivity Index function is used to convert polygon shaped fractures converted to pipe model.

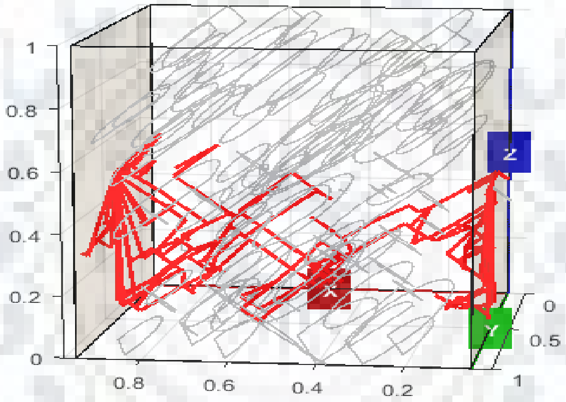


Figure 5.4: application of connectivity field represents connected fractures as pipes in 3D network of our study are in 1m*1m dimensional space

Inlet and outlet in figure 4.4 is defined at midpoint. Similarly, to simulate field condition, a number of simulation can be performed to mimic exact flow condition on field by changing inlet and outlet in fracture network model.

5.3 Flow Simulation in 2/3D domains

After finding preferential flow pathway in fracture network, next step is flow simulation which is carried out in following section. Results of flow simulation in 2/3 dimension is presented which shows flow direction and variation of pressure head across in fracture network at Jabal Akhtar dome in Oman mountains. Different flow direction that can be possible on field is simulated in following section.

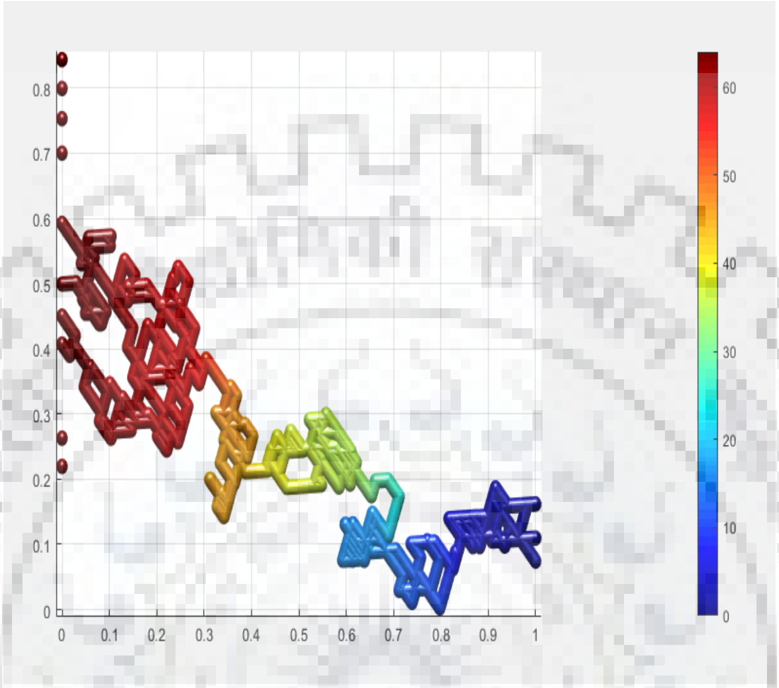


Figure 5.5: 2D fracture model showing flow pathway and variation of pressure head when flow direction is from left to right

Figure 4.5 shows variation of pressure head in fractures when flow is allowed in one direction only with direction of flow taking from left to right and no flow is occurring from top to bottom. This result shows that among different fractures group interconnected in fractured rock at Jabal Akhtar dome in Oman mountains there is only single flow pathway and fluid flow is occurring in 2D through above flow pathway only.

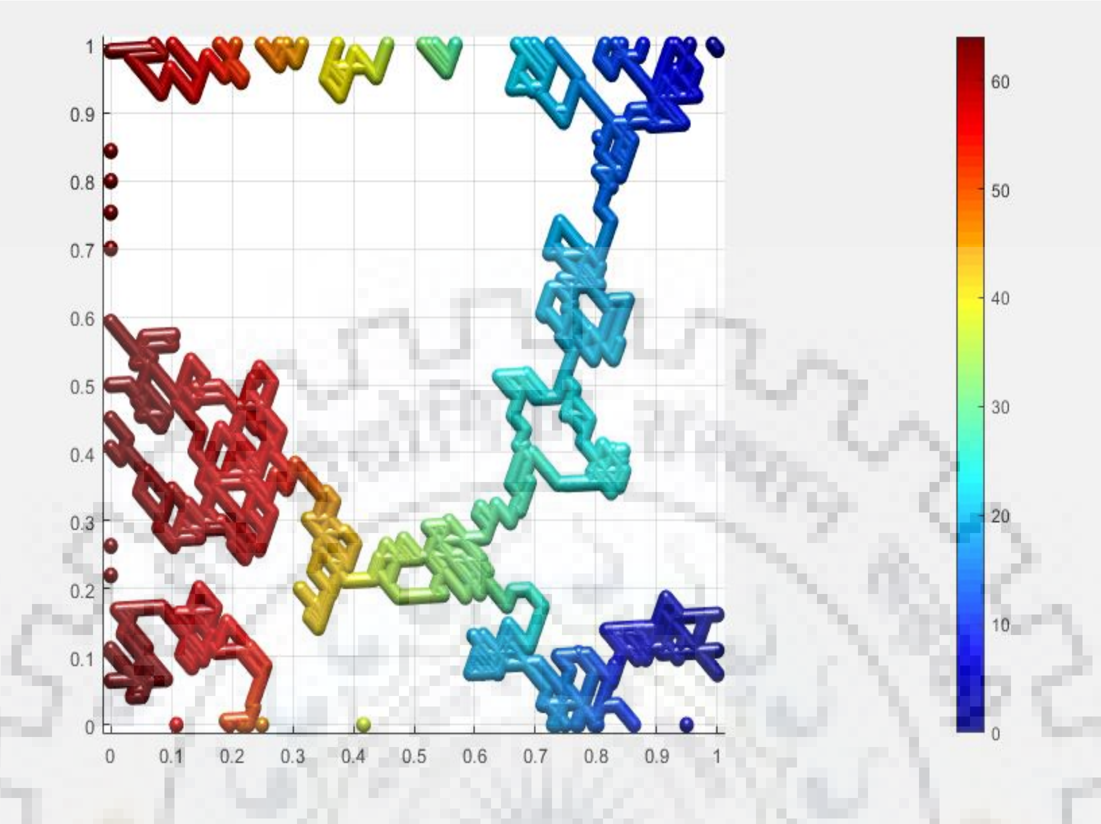


Figure 5.6: 2D fracture model showing flow pathway and pressure head distribution when flow is possible from all direction

Figure 4.6 shows flow pathway and variation in pressure head when flow is allowed from all four directions in 2D fracture network. It shows fracture connectivity and consequent flow pathway from both left to right and top to bottom. There is more than one flow pathway as observed in Figure 4.6 with one flow occurring from left bottom and ending at bottom.

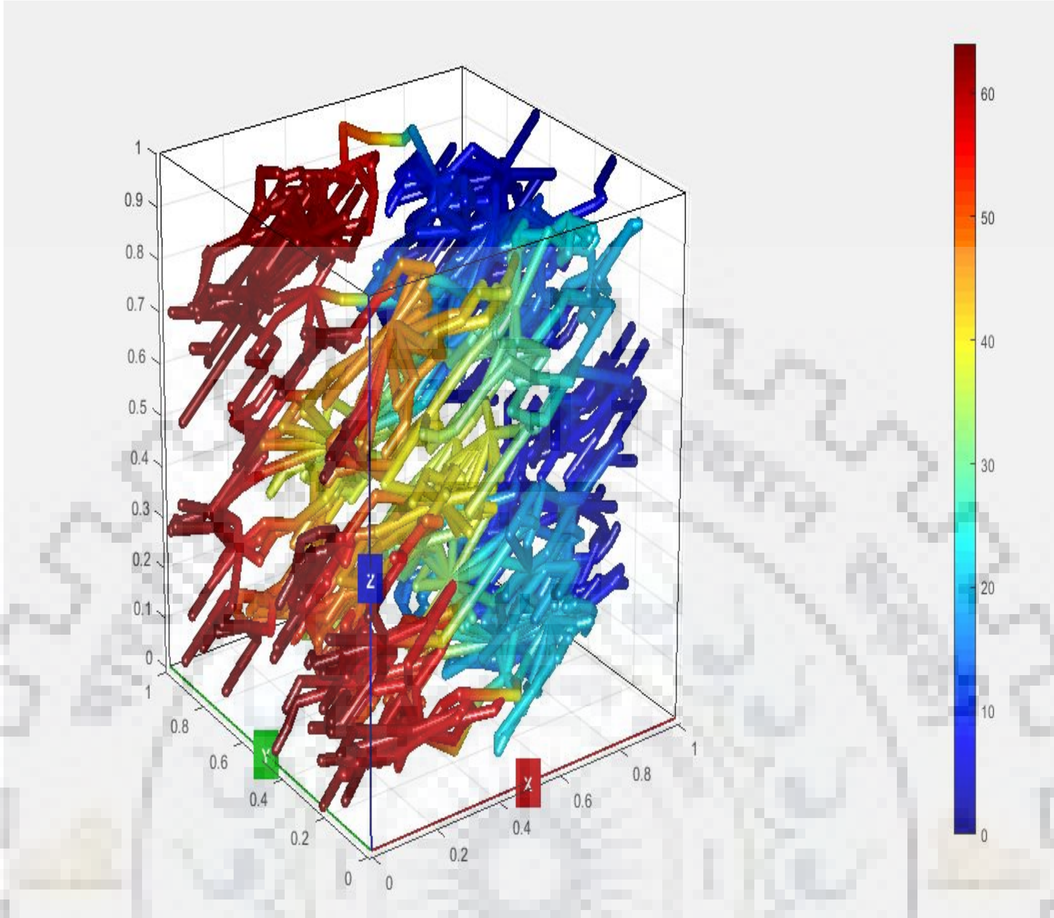


Figure 5.7: 3D fracture model showing pressure distribution when flow simulation is done considering all connected and unconnected fractures.

Flow simulation is performed on all the fractures that are interconnected to form Fracture cluster and direction of flow is taken from left to right. Large number of fractures are represented in blue and light blue color but fewer number of fractures with red color. It represents that in subsurface, in spite of large number of interconnected fractures, not all contributes to subsurface slow.In the next section, fractures which are connected but do not contribute to flow are removed, theory behind it is explained in detail in methodology section and then flow simulation is done.

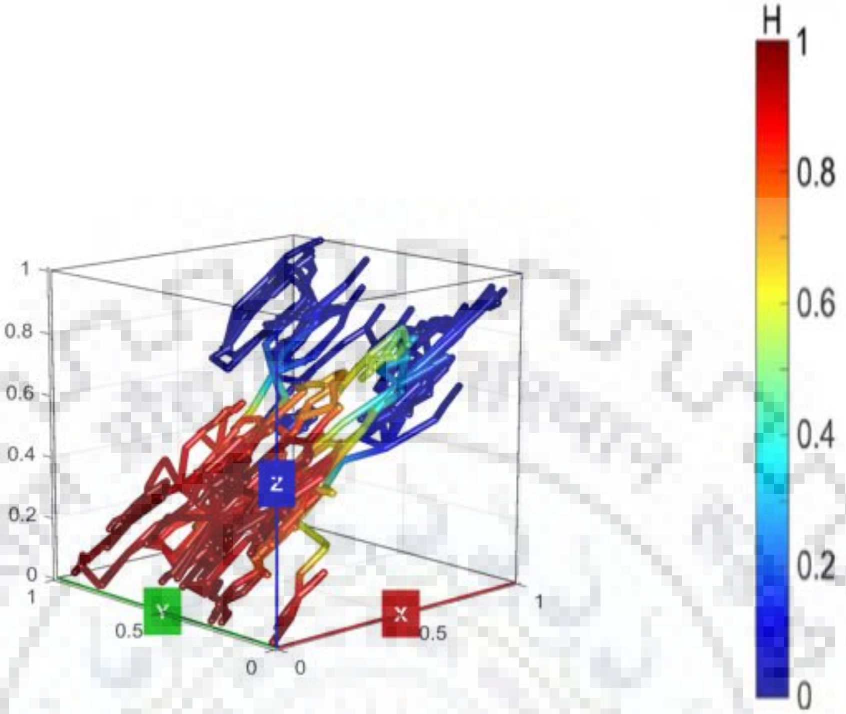


Figure 5.8: 3D fracture model showing flow pathway and pressure head distribution with flow simulation done on those fractures that contributes to flow.

After removing all the pipes that are not contributing flow, flow simulation is performed and result obtained is shown in figure 4.8. Here, flow direction is taken from left to right and variation of pressure head is shown in fracture network. From the figure, it is observed that there is more than one flow pathway in 3D fracture network at Jabal Akhtar dome in Oman mountain. Flow is taking place from bottom to top which is against gravity. However, if flow direction is reversed i.e. from right to left, then flow in fractures will be from top to bottom with only few fractures contributing flow in horizontal direction. Values of fracture network parameters like location, orientation can be varied and different flow simulation models can be prepared that can replicate exact field condition. Above models provide an understanding that in fractured rock, fractures contribute to flow but only those fractures that are connected and through which fluid is flowing.

Chapter 6: Conclusion

In this study DFN approach was used to simulate water flow through a fractured rock mass by considering each fractures individually. This approach has flexibility of modeling using both deterministic and stochastic techniques. Trace line map produced from satellite image of Jabal Akhtar dome situated in Oman mountains was developed using FraNEP simulator. Three different sampling methods (window, scanline, and circular estimator) were used to evaluate 2D fracture characteristics of the rock mass. Circular sampling method had more variation in values of fracture density, fracture intensity due to small radius taken to perform the sampling which should be more than 45m to get result to be synchronous. Values of window sampling and scanline sampling were found to be nearly same. The scanline sampling method was incapable of calculating total number of fractures and their density in the study domain, the window sampling was further used for fracture characterization of the study domain. For flow simulation, stochastic approach of DFN was used and fractures in 2D were represented as straight line segment. The fractures were represented in polygon shape in 3D representation of the domain and exponential distribution function was used to define the length and size of fractures. Every fracture was distributed into the space by rotation using Von-mises distribution function for 2D and Fischer distribution for 3D case. Additional characteristics like aperture of fracture was taken 0.5 mm and surface roughness was ignored based on the field situation. Different functions using MATLAB were developed to perform the stochastic modeling in 2D and 3 D forms of fracture network. Intersection analysis, density measurement, clustering of fractures etc were also performed using the suitable MATLAB functions. Connectivity index was then developed for evaluating the interconnection of the fractures in the modeled multi-dimensional network.

Analysis of the connectivity of the fracture network is an important component of design and development of fracture-based flow model which is neglected in other conventional modeling approaches such as equivalent porosity method and dual porosity method. Flow simulation model prepared in 2 D form shows that flow pathways are existed both in horizontal and in vertical directions. Similarly, three dimensional model shows a clear flow pathway of water flux from surface rock to the underlying subsurface zone. This modeling can be performed to any field scale and helps in simulating possible flow pathways through fractured rocks and can be used to determine those fractures that contributes to flow process.

6.1 Future scope of work

Inclusion of permeability of fractures and effect of impermeable zone in between fracture connectivity and its effect on mechanisms of fluid flow are the key challenges that can be considered in future work. Effect of gravitational drainage and capillary effect on fluid flow are not considered in our present study and surface roughness of fracture is also neglected. These are the factors that can considered for further improving the identification of flow pathways and for flow quantification in a fractured domain.

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