

# Developing a 3D stochastic discrete fracture network model for hydraulic analyses

Ali Heydari <sup>a,\*</sup>, Seyed Esmaeil Jalali <sup>a</sup> and Mehdi Noroozi <sup>a</sup>

<sup>a</sup> Faculty of Mining, Petroleum and Geophysics Engineering, Shahrood University of Technology, Shahrood, Iran

## Article History:

Received: 29 October 2017,

Revised: 12 May 2018,

Accepted: 24 June 2018.

## ABSTRACT

Fluid flow in a jointed rock mass with an impermeable matrix is often controlled by joint properties, including aperture, orientation, spacing, persistence, etc. On the other hand, since the rock mass is made of heterogeneous and anisotropic natural materials, the geometric properties of joints may possess dispersed values. One of the most powerful methods for simulation of the stochastic nature of joints geometric characteristics is three dimensional stochastic discrete fracture network (DFN) modelling. The main goal of this research is development of a method and an instrument for hydraulic analyses of complicated DFN. For this purpose, DFN-FRAC<sup>3D</sup> program – which has been proposed for mechanical analyses – was developed to construct a hydraulic DFN. The joint aperture parameter was added to other geometric features of the model and to increase the accuracy, the correlation between the joint aperture and the length was considered. In addition, the program was developed for detecting the connected joint networks. In the next step, the connected joint networks were converted to equivalent pipe networks. Finally to study the fluid flow within this network, WaterGEMS, a Numerical software for flow modeling, was used that had the capability to make complex pipes and to receive other hydraulic information. In order to test the performance of the provided program, a 3D hydraulic model was presented for fractured networks of the rock mass in the Mazino region. It can be concluded that in the case of executing the Underground Coal Gasification panels in the Mazino coalmine of Central Iran, the resulting gases will not leak to the ground.

**Keywords :** Mineral Resource Evaluation, Kriging, Epistemic Uncertainty, Fuzzy variogram, Extension Principle, Jajarm Deposit

## 1. Introduction

The first step in studying the behavior of fluid migration in a jointed rock mass is to build a geometric model of the joint network that is proportional to the surveyed data. Since the rock mass is composed of heterogeneous and anisotropic natural materials, the geometric properties of joints, including orientation, persistence, and spacing, may possess dispersed values. Therefore, it is necessary to consider the stochastic nature of these characteristics and to use them in the modelling process. One of the most powerful methods for simulating the stochastic nature of joints geometric characteristics is the Discrete Fracture Network (DFN) three-dimensional stochastic modelling method [1]. Producing a discrete fracture network requires the knowledge about joint properties, including the number, orientation, spacing, persistence, aperture and joint intensity. The DFN 3D geometrical-stochastic modeling method has several applications associated with structural design, surveys of water resource, nuclear waste storage, enhanced oil recovery, underground CO<sub>2</sub> storage and hydrocarbon reservoirs design in jointed rock masses [2].

In hydraulic analysis of a jointed rock mass, if the matrix permeability is lower than the joint permeability, some joint properties, such as permeability and joint aperture, are the fundamental units of controlling the flow behavior and fluid transport [3]. In nature, in most of geological structures, compared to the permeability of fractures in the rock mass, the rock matrix permeability is very small and the fractures are the main routes of flow. In such a situation, the fractures control the behavior of fluid flow in the rock mass and its assessment requires a proper understanding of the hydraulic behavior of fracture networks.

Currently, several software, such as FRACMAN, FARACA, and NAPSAC, have been developed for stochastic modeling of a rock mass that are applicable in rock mechanics studies, especially in flow modeling and in estimation of the rock mass permeability. In this paper, DFN-FRAC<sup>3D</sup> computer program [1, 4, 5] was used to build a DFN model. Hitherto, DFN-FRAC<sup>3D</sup> has been proposed to provide a geometric model for mechanical analyses. In this study, this program was developed to construct a DFN model suitable for hydraulic analyses (hydraulic DFN). For this purpose, the joint aperture parameter was added to the program, considering the fact that it takes into account the correlation between the joint aperture and length, as well as its ability of detecting the connected joint networks.

After developing the DFN model, there are two approaches for numerical simulation of a flow. One approach is to convert the DFN to a network of pipes with features conductivities, flow rates, and hydraulic properties almost similar to the joint planes [6]. The other approach is an accurate discretization (triangulation) of joint planes as finite elements and using the finite element method (FEM) [7]. There are several commercial software packages for modeling the fluid flow using either of the above-mentioned methods. Discretizing the fractures into grids is the more complicated approach since the aperture variations in each fracture plane are important. Moreover, this is a very computationally difficult approach, since the flow equations have to be solved for each grid element [8]. In this study, the DFN-FRAC<sup>3D</sup> program was developed to convert the hydraulic DFN to an equivalent pipe network. The program's output was meant as a commercial software. Finally, for modeling the fluid flow, the WaterGEMS commercial software was used.

\* Corresponding author. Tel: +98-9120640556, E-mail address: ali.heydari84@yahoo.com (A. Heydari).

## 2. Literature Review

Simulation of the flow and fluid transport in jointed media is a widely concerned topic in the field of rock mechanics. Fluid flow in jointed rock masses are commonly controlled by joint properties (i.e., aperture, orientation, persistence, spacing, etc.). In this field, many issues are not properly recognized that require further researches [9]. Moreover, due to the complexity of involved configurations and due to the seepage properties of 3D fractures in real fractured rocks, the development of 3D hydraulic DFN models is slow [9].

In recent decades, many efforts have been made to understand the behavior of fluid flow in a rock mass [10, 11]. Although, accurate estimation of the rock mass permeability is still a challenging issue because of the complexity of joints distribution in macrostructures (i.e. joint network geometry) and microstructures (i.e. pore spaces of individual joints' geometry) [12]. The history of DFN flow models dates back to almost 30 years ago when Long et al. 1982 developed a 2D model [13]. Table 1 describes some of the recently proposed DFN models for estimation of flow transport in a jointed rock mass.

**Table 1. Some of the recent DFN models proposed to estimate the fluid flow and transport**

No.	Researcher	2D or 3D	DFN generator	Flow solution	Connected Joint network	Joint shape	Joint aperture
1	Ito and Seol, 2003 [14]	3D	Development of new code (FracMesh)	Commercial software (TOUGH2)	No	Rectangular	Correlated with joints' length
2	Baghbanan and Jing, 2007 [11]	2D	Development of new code	Commercial software (UDEC)	No	linear	Correlated with joints' length
3	Bodin 2007 [8]	2D	Development of new code (SOLFRAC)	Pipe network method	Yes	linear	Fixed
4	Iding and Ringrose, 2008 [15]	3D	Development of new DFN model	Commercial software (Eclipse)	No	Rectangular	Fixed
5	Bang et al., 2012 [16]	3D	Development of new DFN model	Channel network method	Yes	Circular	Correlated with joints' length
6	Javadi and Sharifzadeh, 2012 [17]	2D	Development of new code (FNETF)	Finite Element Method	Yes	linear	Fixed
7	Bigi et al., 2013 [18]	3D	Commercial software (Petrel)	Commercial software (Comsol)	Yes	Circular	Fixed
8	Zhang and Yin, 2014 [9]	3D	Development of new DFN model	Finite Element Method	Yes	Polygonal	Fixed
9	Li et al., 2014 [19]	2D	Commercial software	Pipe network method	Yes	linear	Fixed
10	Xu et al., 2014 [20]	3D	Existence code	Pipe network method	No	Polygonal	Fixed
11	Lee and Ni, 2015 [3]	3D	Development of new DFN model	Commercial software (TOUGH2)	Yes	Circular	Fixed
12	Hyman et al., 2015 [21]	3D	Development of new code (DFNworks)	Commercial software (Pflotran)	Yes	Circular	Fixed
13	Huang et al., 2016 [22]	3D	Commercial software (3DEC)	Finite Element Method	No	Circular	distribution function
14	Ren et al., 2017 [23]	3D	Existence code	Pipe network method	Yes	Circular	Fixed
15	Alghalandis, 2017 [24]	3D	Existence code (GenFNM3D)	Pipe network method	Yes	Polygonal	Fixed

Given the significance of development of 3D DFN flow models, this study is focused on simulating a flow in a 3D discrete fracture network. The shaded cells in Table 1 show some simplifications of previous models and simulators, as well as the differences between the simulator presented here and previous researches. In most cases, joint apertures are considered to be fixed. In some cases, the joints are assumed to be circular. Indeed, since rocks are generally inhomogeneous, the formation of completely elliptical joints is less likely. In addition, as joints end at the intersection with each other, the observed joints are in a polygon shape [2]. In this study, in order to test the performance of the provided simulator, a 3D DFN model was presented for the fracture network of rock masses in the Mazino coalmine in Central Iran to survey the gas leak from an Underground Coal Gasification (UCG) georeactor.

## 3. DFN-FRAC<sup>3D</sup> program

We wrote the DFN-FRAC<sup>3D</sup> program in C++. The program is composed of 14 classes, 110 functions, and more than 3000 lines (Figure 1).

In the DFN-FRAC<sup>3D</sup>, the joints were convex polygonal planar objects of a discontinuous rock, randomly oriented and located in 3D spaces. In this program, the Poisson plane and the line stochastic processes were incorporated together. A joint set was generated in the modeling space by applying a sequence of four stochastic processes, as follow:

- First process: a homogeneous Poisson network of planes in

space.

- Second process: sub-division of each plane into a jointed region and its complementary region of intact rock by a homogeneous Poisson line network.
- Third process: non-homogeneous polygon production procedure on created polygons in the previous step based on the shape and size.
- Fourth process: random shifting of the polygons that were marked as jointed near their original position.

A joint system, including joint sets, is generated with reiteration of the presented processes.

The DFN-FRAC<sup>3D</sup> has most of the features of commercial and computer software packages developed so far. The program is capable of using the collected data to display the joints network graphically in different directions in addition to produce digital outputs. Some sampling tools such as bedding and core samplings have been provided in this program to determine the credibility level of the model. This program can create cross sections in different directions and it statistically investigates the effect of joints on the cross sections. The provided program can produce joints in a greater area than the considered area to remove the boundary effects in which only some of the joints are supposed to be modelled. The program receives the distribution functions of joint persistence, dip, and dip direction as input values and generates them in the considered area with different sizes and arrangements. The following items are of other important features

of the DFN-FRAC<sup>3D</sup> that are not available in other similar programs:

a) *Random sampling*: the proposed program can obtain 3D random samples with customized size from a preliminary large sample.

b) *Faulty region modeling*: the developed program can provide 2D and 3D DFN models of faulty regions where the joint density varies linearly or exponentially by moving away from the fault plane.

c) *Considering co-planarity properties*: most of previously proposed models lack this feature. It is only available in complex models and some commercial software packages, which is a great advantage.

More details about the software and its applications can be found in references [1, 4, 5].

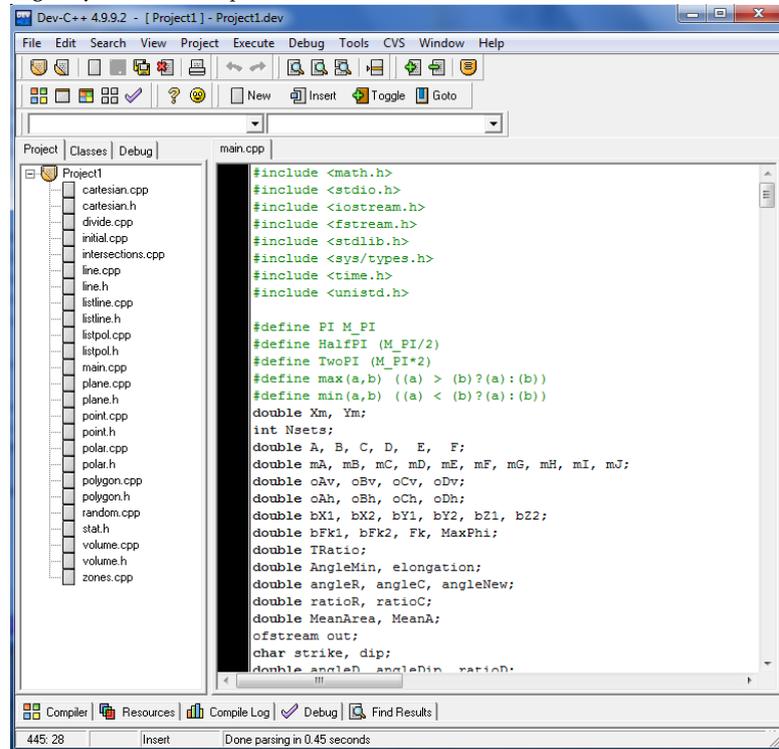


Figure 1: DFN-FRAC<sup>3D</sup> software applicable to a Dev-C ++ compiler [2]

## 4. Development of DFN-FRAC<sup>3D</sup>

### 4.1. Joint aperture

Joint geometric parameters including orientation, spacing, persistence, intensity, average size and shape are the input values of the DFN model. Since the DFN-FRAC<sup>3D</sup> software is so far intended for mechanical analyses, the joint geometric features are to meet the needs of the DFN models.

On the other hand, an aperture is a geometric property of a joint that has a crucial impact on hydraulic behavior of the rock mass. When there is no change in fluid properties, i.e. it remains incompressible, isothermal, and single-phase, the potentials of hydraulic conductivity and flow transport of the rock mass would be a function of joint aperture. Therefore, considering the purposes of this study, the joint aperture parameter, as a geometrical feature of a joint, is considered in the DFN model.

Generally, it is assumed that the joint aperture follows a lognormal distribution function [11, 16]. Probability Density Function (PDF) of lognormal distribution of a joint aperture ( $h$ ) can be written in the following general form:

$$f_A(h) = \frac{1}{h\sigma\sqrt{2\pi}} e^{-\frac{(\ln h - \mu)^2}{2\sigma^2}} \quad (1)$$

Where,  $\mu$  and  $\sigma$  represent average and standard deviation of natural logarithm of joint aperture, respectively. Cumulative Distribution Function (CDF) of lognormal distribution of joint aperture is as follows:

$$F_A(h) = \frac{1}{2} + \frac{1}{2} \operatorname{erf} \left[ \frac{\ln h - \mu}{\sigma\sqrt{2}} \right] \quad (2)$$

Where, erf is the error function and may be in the following form:

$$\operatorname{erf}(h) = \frac{2}{\sqrt{\pi}} \int_0^h e^{-t^2} dt \quad (3)$$

### 4.2. Correlation of Joint Persistence and Aperture

So far, some researchers have shown the relationship between the joint trace length and the joint aperture, based on joint properties obtained from field surveys. The obtained relationships indicate that there is no valid general rules for the correlation between the joint length and aperture. However, previous studies indicate that the joint length and aperture are actually correlated even if there is no universally accepted correlation function [11].

Assuming that the probability density function for lognormal distribution of a joint aperture ( $h$ ) is  $f_A(h)$ , Truncated Cumulative Distribution Function (TPDF) for lognormal distribution of a joint aperture is as follows (Bang et al., 2012):

$$f_{TA}(h) = \frac{f_A(h)}{\int_{h_a}^{h_b} f_A(t) dt}, \quad h_a \leq h \leq h_b \quad (4)$$

Where,  $h_a$  and  $h_b$  represent the upper and lower limits of the joint aperture, respectively. It should be noted that since joint measurement methods have upper and lower identification limits, the distribution functions commonly have a sampling bias, which is known as the truncation threshold. In numerical modeling, using the joint system surveyed data, the application of truncated distribution of the joint aperture and length is inevitable because it is a direct consequence of in situ joint surveying.

Truncated Cumulative Distribution Function (TPDF) for lognormal distribution of a joint aperture would be as follows:

$$F_{TA}(h) = \int_{h_a}^h f_{TA}(t) dt = \frac{\int_{h_a}^h f_A(t) dt}{\int_{h_a}^{h_b} f_A(t) dt} = \frac{F_A(h) - F_A(h_a)}{F_A(h_b) - F_A(h_a)} \quad (5)$$

$$h_a \leq h \leq h_b$$

In a very similar approach, similar relationships will be obtained for

Truncated Cumulative Distribution Function (TPDF) of the joint length distribution.

To consider the correlation between the joint length and aperture, it is assumed that the TCDF of lognormal distribution of the joint aperture ( $h$ ) has a randomly count similar to that of the joint length ( $l$ ) [16]. Therefore, the joint length and aperture correlation function can be expressed in the following way:

$$\frac{F_A(h) - F_A(h_a)}{F_A(h_b) - F_A(h_a)} = \frac{F_L(l) - F_L(l_a)}{F_L(l_b) - F_L(l_a)} \quad (6)$$

Where,  $F_L(l)$  is the cumulative distribution function of lognormal distribution of the joint length, and  $l_a$  and  $l_b$  respectively represent the upper and lower limits of the joint length.

In fact, when the joint aperture and length are correlated, the general

dip	strike	radius	aperture
35.2377	-162.281	2.64547	0.0062875
35.2377	-162.281	5.51795	0.00814375
35.2377	-162.281	5.26069	0.00814375
35.2377	-162.281	14.985	0.00984531
35.2377	-162.281	4.98484	0.00783438
35.2377	-162.281	18.9578	0.01
54.0596	-138.828	0.796124	0.00303906
35.2377	-162.281	2.60895	0.0062875
35.2377	-162.281	13.2235	0.00969063
35.2377	-162.281	1.52171	0.00474063
19.7997	-162.589	9.78257	0.00938125

Figure 2. Output values of joint aperture vs. generated joint radius based on their statistical correlation.

#### 4.3. Detection of Connected Joint Network

One of the problems of a discrete fracture modeling approach is that there is a large number of modeled joints in the field. Usually, the modelling process faces some system memory limitations while attempting to present all generated joints accurately. In order to create a flow simulation model, the model has to be able enough to simulate the flow process in which the generated production rate can be compared with the production history observed in the field.

To identify the connected joint networks, a highly detailed static joints model is produced at first, and then, the DFNs of significance to flow (connected joint networks) are detected in the model. The isolated networks, or those that are partially connected to other joints or input/output flow boundaries, will be deleted. The detection process of nonconductive joints is a recurring iterative process. This is because removing a piece with a dead-end point can change other available network pieces to isolated joints or isolated pieces with new dead-end points. Accurate application of the elimination process results in a simpler network with significantly less intersecting joints.

Afterward, the remaining DFNs can be converted to the flow simulation models using the pipe network or the channel network methods to obtain accurate results on fluid permeability. This is a quick method and only needs to consider the flow lines and calculate the fluid transport time. More importantly, this method can simulate the most significant behaviors in the early stages of the flow history, only by considering the connected fractures network.

In the current research, the DFN-FRAC<sup>3D</sup> software was developed for detection of the connected joints network. The methodology is as follows. In the first iteration of joints modification, the open end and isolated joints are removed. These joints are shown with number 1 in Figure 3. An intended criterion to detect these joints is the number of joints that are connected to the considered joint. If the number of joints connected to the considered joint is greater than or equal to 2, it is a hydraulic joint, otherwise it will be removed. The algorithm used for DFN-FRAC<sup>3D</sup> software development, in order to detect hydraulic joints, is shown in Figure 4. In the following joint modification iterations, open end joints are removed. The removed joints in iterations 2 and 3 of the

permeability of different stochastic models is much larger than when they are not; in this case, non-correlated properties simplify the numerical modeling [11]. However, in most of the previous studies that used the DFN model, it is assumed that there is no correlation between the joint aperture and length [16]. This study considers the correlation between the joint aperture and length to accurately build the DFN model for further hydraulic analysis for which the DFN-FRAC<sup>3D</sup> program was developed.

In the DFN-FRAC<sup>3D</sup>, using equation (6) and employing negative exponential, lognormal, and gamma cumulative distribution functions of the joint aperture and length, the aperture values vs. length values of all the joints are calculated and printed in a separate file (Figure 2).

algorithm are shown in Figure 3. This process continues until all open-end joints and thus all dead-end routes will be removed (except those connected to the defined flow boundaries). The remaining joints are the ones that affect at least one route, which connects two boundary planes.

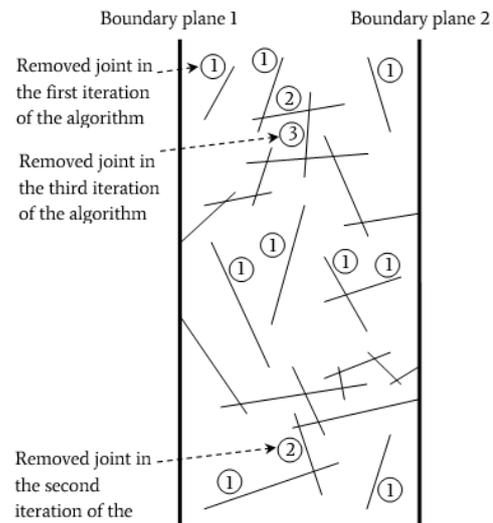


Figure 3. Removed joints in different stages of the algorithm iterations (removed joints in the first iteration of the algorithm)

Figure 5 is an example of an implemented DFN model with the detected connected joint networks. The large model dimensions are  $100 \times 100 \times 100 \text{ m}^3$  and include 4 joint sets and 3402 joints (Figure 5a). The hydraulic model, including a cube with  $60 \times 60 \text{ m}^2$  footprint and 40 m height is selected from the center of the DFN model. Flow boundary planes are selected, which are horizontal planes at the bottom ( $z=30$ ) and up ( $z=70$ ) of model. After running the hydraulic model, 612 connecting joints of flow boundaries are detected (Figure 5b).

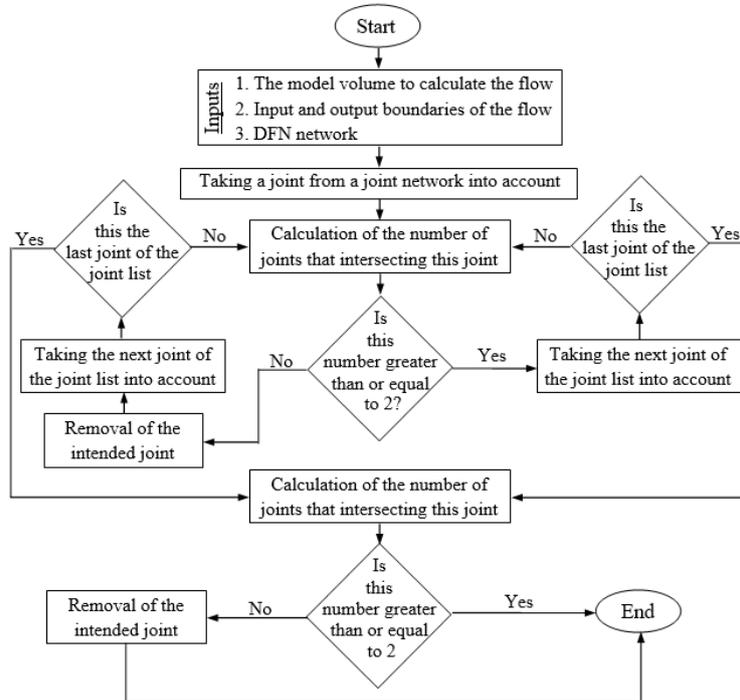


Figure 4. Algorithm of single and dead-end joints removal in DFN model

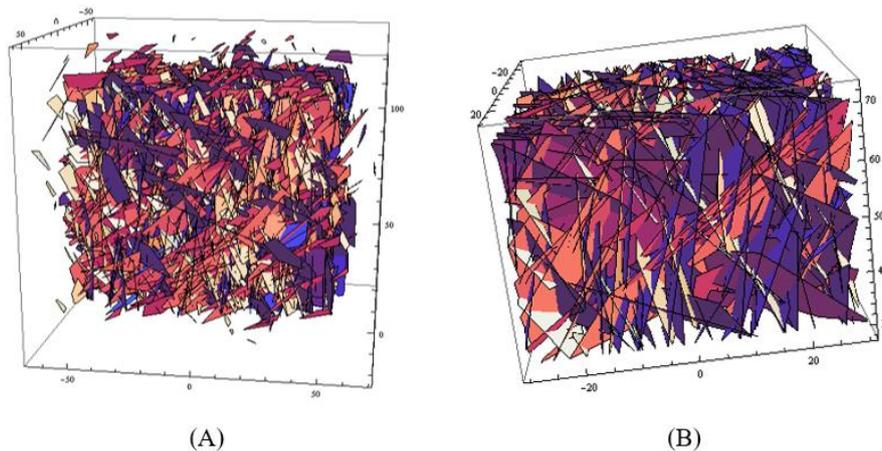


Figure 5. A) DFN with all joints, B) hydraulic DFN after removal of non-connected joints

#### 4.4. Equivalent pipe network

Reducing the 2D or 3D problems to one dimensional ones in modeling the flow and transmission in pipe networks is more computationally efficient. In this method, a pipe network was constructed out of a 3D discrete fracture network model. In general, the basis of the equivalent pipe network method is the replacement of rock fractures with pipes that have the same flow of fluid equivalent to that of the fractures. The process of forming the pipe networks in the DFN-FRAC<sup>3D</sup> is as follows:

1. Considering a joint.
2. Finding a joint / joints that intersects it.
3. Finding intersection lines (joints with each other and joints with flow boundaries).
4. Finding the middle point of the intersection lines.
5. Creating a line between the middle points of the intersection lines and the center of the joint (creation of pipes with beginning and end coordinates) (Figure 6).

6. Calculating the length of the tubes (L) and the total length of the tubes (L<sub>tot</sub>). It is assumed that all tubes on a joint have the same diameter.

7. Calculating the equivalent pipe diameter based on the following equation (in this case, the total joint surface is assumed to be involved in fluid transfer).

$$d = \sqrt{\frac{4 \times A \times e}{\pi \times L_{tot}}} \quad (7)$$

Where, A is the area and e is the joint aperture.

The pipe network model containing 8813 pipes is shown in Figure 7, which is equivalent to the joint network shown in Figure 5. In this model, cross-connecting pipes with an up and down boundaries are connected to two points by virtual pipes. These virtual pipes are assumed to be non-frictional for flow analysis. In this way, the input pressure/head can be applied at a first point and measured at the end point.

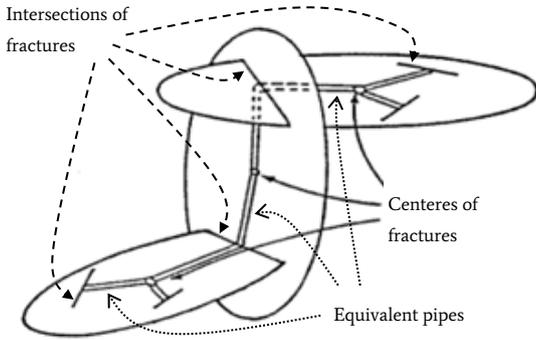


Figure 6. Conceptual model of a pipe network resulting from the intersection of several joints

4.5. Flow analysis

For analysis of the pipe network, the Bentley WaterGEMS V8i commercial software was selected. It is noteworthy that a lot of pipe network software packages are limited by the number of pipes. Meanwhile, the chosen software is a rare one without this limitation. To use this software, the output of the DFN-FRAC<sup>3D</sup> program has been developed for this purpose. The output file includes the start and end points, diameter and length of pipes (Figure 8). The pipe information (DFN-FRAC<sup>3D</sup> program output) is converted by the Rockwork software into a dxf file to enter the GIS environment. In the GIS software, the diameter of each pipe is added as an attribute. Then, the Bentley WaterGEMS software calls the GIS output file. When the pipe network is made in the software, the nodes' coordinates are re-generated. In this step, two reservoirs are defined at the start and end points and a suitable pump is placed at the start point of the network to supply the pressure of the reservoir. Finally, a flow analysis is carried out on the network.

The output of the software is as an Excel file in which the graphical outputs include flow direction, flow path, input and output pressure, inlet and outlet flow for the whole network and each pipe. The flow analysis of the pipe network in Figure 7 (joint network in Figure 5) is shown in Figure 9. In this example, the input pressure is assumed to be 1 MPa, and the pressure at the end point was obtained 0.6 MPa.

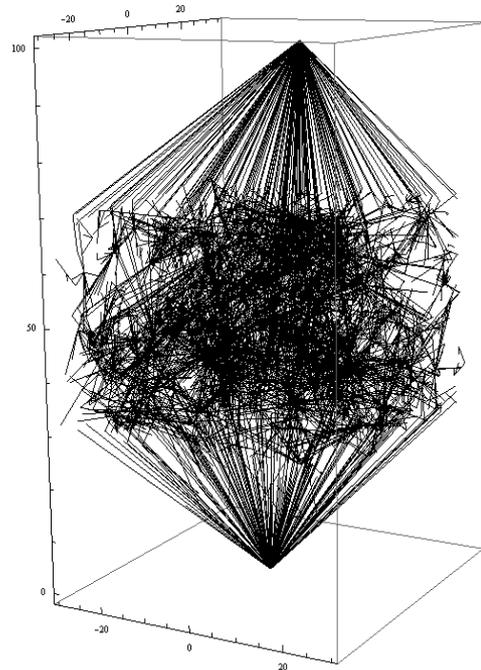


Figure 7. Pipe networks model equivalent to the discrete fracture network of figure 5b

Figure 8. Program output include start and end points, diameter and length of pipes

5. Case Study: Mezino Coal Region in Tabas

In Iran, most of the coal reserves are located deep in the ground or they are very thin layered. To extract and use these sources of coal, Underground Coal Gasification (UCG) seems to be the best option. One of these coal reserves is the coal-bearing strata of Mazino in Tabas, Central Iran. 8800 km<sup>2</sup> of the Tabas coal reserves is located in Mezino. The Mezino coal deposit is situated 85 km west of Tabas, Yazd Province. The Mezino region is identified with 75 coal-bearing stratals. The Mezino Formation contains sandstone, shale and siltstone units that the coal layers are laid within this formation. Mezino coals are of anthracite and semi-anthracite types. The coal layers dip is less than 30°. Among the Mezino coal bearing strata, M2 has the highest priority for implementing the UCG, because of its high thickness and the large amount of it coal reserve. Besides, it has the potential of providing the synthesis gas to a 200 MW power plant for more than 100 years. The layer height and depth are 3.5 m and 600 m, respectively, and the proven reserve is 139 million tonnes [25].

Modeling the joint network in the Mezino region was performed using the DFN-FRAC<sup>3D</sup> software as well as the geometrical parameters of the field data (Table 2). This model contains 269.623 joints in a 45×45×600 m<sup>3</sup>, as shown in Figure 10a. The hydraulic model, including a cube with 40 × 40 m<sup>2</sup> footprint and 600 m height was selected from the center of the DFN model. Flow boundary planes (horizontal planes) were selected at the bottom (z=5) and top (z=595) of the model. After running the hydraulic model, 6,355 connecting joints of flow boundaries were detected (Figure 10b).

Table 2. Joint parameters employed in development of DFN model for Mezino region

Joint set	Dip/DipDirection (°)	Fisher constant	Fracture Intensity (m <sup>-3</sup> )	Mean persistence (m)	Mean aperture (mm)
1	38/088	58.6	1.17	4.587	1.953
2	87/228	22.7	0.18	0.375	1.092
3	75/276	22.6	0.14	0.386	1.095
4	82/174	36	0.04	0.361	0.852

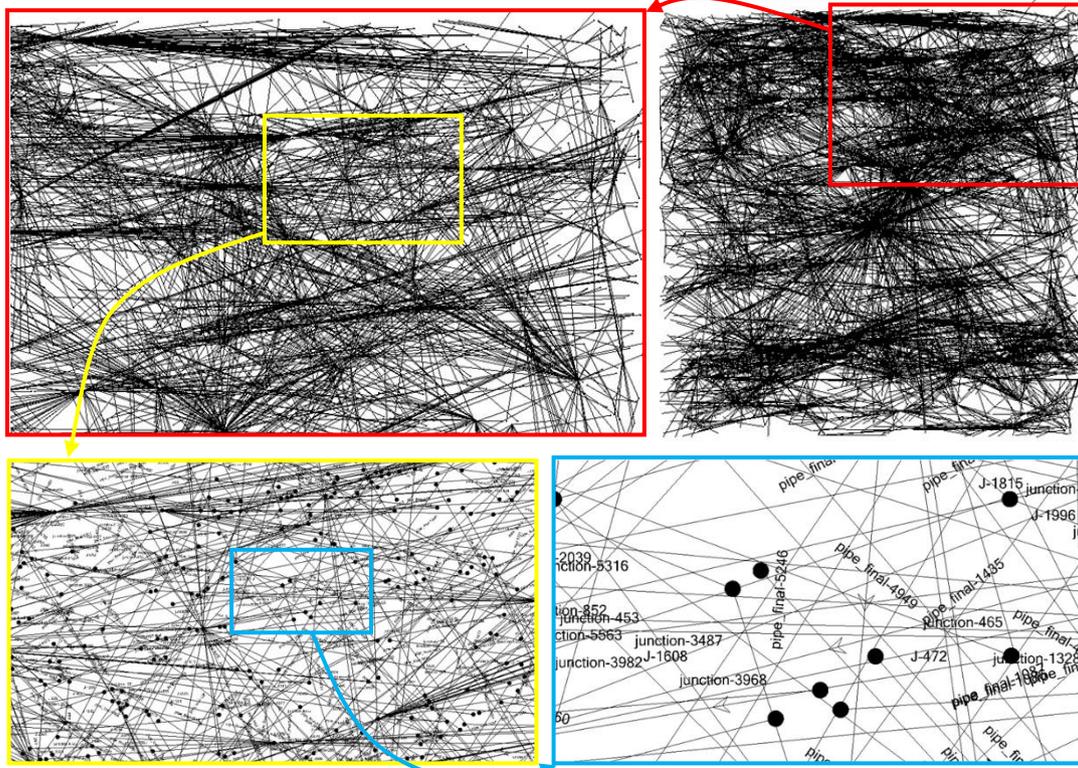


Figure 9. Pipe networks and flow directions in the Bentley WaterGEMS software

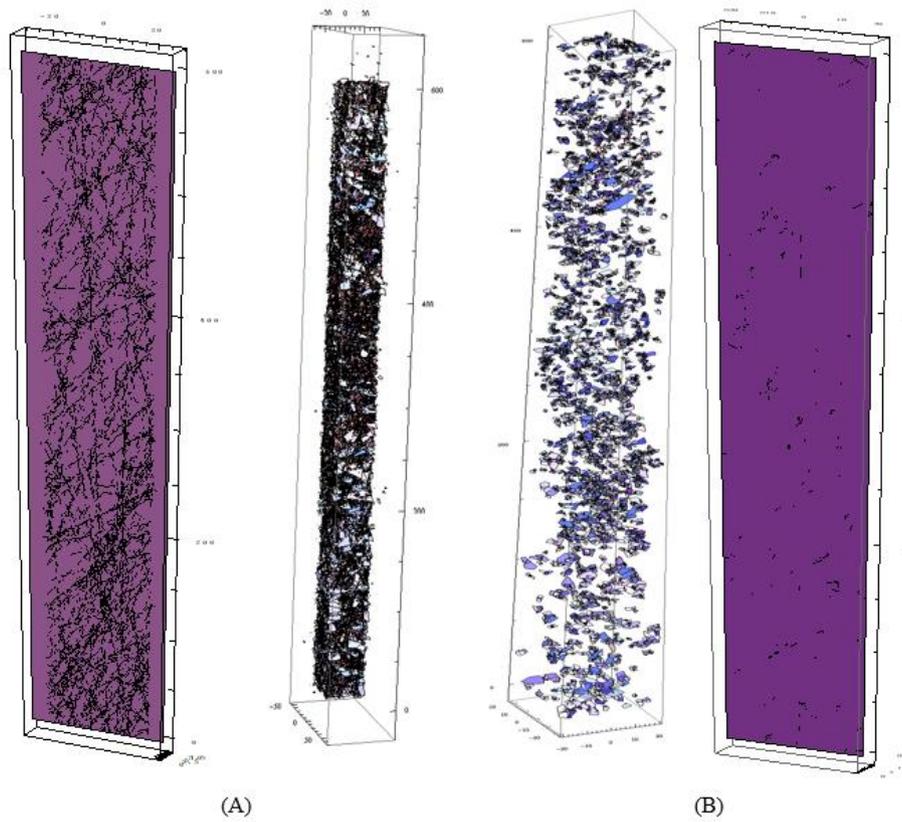
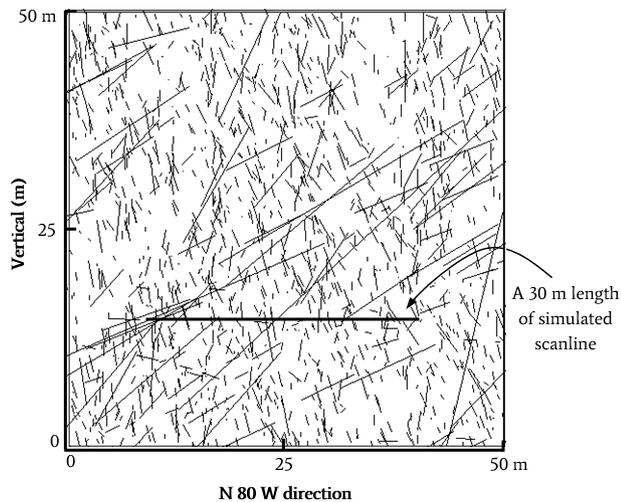


Figure 10: A) DFN network for Mazino region with all available joints, B) hydraulic DFN network

In order to validate the prepared DFN model, the simulated joints were compared with the observed joints. Figure 11 shows the joint traces obtained from the joint networks intersection with a 50 m vertical

square window having the same direction as that of the scanline and was placed in the middle of the DFN model cube. A 30 m long scanline was simulated in Figure 11. The 1-D joint frequency on this simulated

scanline was about 1.3 joints per m. This value quite well compared the observed 1-D joint frequency of 1.6 joints per m on actual scanline. These findings shows that the generated 3-D stochastic joint networks model is in a good agreement with the actual fracture system.



**Figure 11. Joint traces on a vertical outcrop having the direction same as the trend direction of scanline**

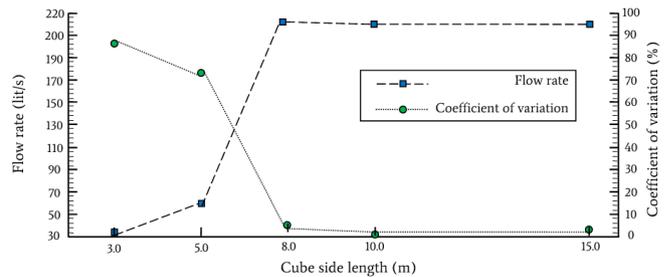
As shown in Fig. 10b, connected joints do not connect the lower and upper boundaries of the model. In other words, in some areas of the model, the joints are not interconnected and the joints of the model are not completely connected to each other. Therefore, it can be concluded that as the UCG in the Mazino coal mine in executed, the resulting gases will not leak to the ground. For the sensitivity analyses and with the aim of establishing a fully connected network of joints between the lower and upper boundaries, the joint network model was re-developed for the Mesino area with a 50% increase in the joint volume intensity. The new model consists of 347,288 joints in which 10,451 connected joints have been created. In the new model, the connected joints are fully linked to each other and are connect the lower and upper boundaries of the model. On the other hand, due to the huge number of pipes in the model (more than one million), the DFN-FRAC3D program is not capable of pipe network creation. In addition, no commercial software is able to analyze such a model. Therefore, it was decided to make the REV model based on the new DFN model. By definition, the smallest size of the model, in which there are sufficiently many heterogeneities to fix equivalent properties of a rock mass in frequent experiments, is called REV. In other words, the specific feature of a rock mass (mechanical, hydraulic or thermal) in a REV size is equal to all sizes larger than REV.

In this paper, 5 sizes of cube samples with dimensions of 3, 5, 8, 10 and 15 meters were considered. For each sample size, at first, the original DFN model and subsequently the hydraulic DFN model (connected joints) were provided. Then, the tube network model was created. Finally, the pipe network model was analyzed using the WaterGEMS commercial software and the flow rate was calculated. The results for the different sample sizes are shown in Figure 12. The flow rate for the smallest sample with a dimension of 3m×3m×3m was estimated to be 31 lit/s. For the case study of this research, the size of the REV was 8m×8m×8m. In sizes larger than this, the flow rate changes were negligible. Based on the REV size, the average flow rate of the studied rock mass was estimated at 212 lit/s.

## 6. Conclusion

In this paper, a DFN flow model was proposed for hydraulic applications. To do so, the DFN-FRAC<sup>3D</sup> computer program was developed for hydraulic analyzes, which had been intended for mechanical purposes, so far. Accordingly, the statistical feature of aperture, the correlation between the distributed fracture aperture and length, and the detectability of connected joints were added to the software. Each joint was converted into an equivalent pipe based on its

area and its aperture. Then, the pipe network model was created with respect to the joints intersections with each other. The required algorithms and flowcharts were generated to develop a hydraulic DFN model. In the next step, the pipe network model was analyzed using the WaterGEMS commercial software and the pressure and flow rates were obtained. The developed program, for the purposes of drainage, underground water extraction, and enhanced oil and gas recovery, the location of holes could be proposed based on flow analysis of this software. This program requires no discretization processing which makes it highly efficient without loss of precision.



**Figure 12. Flow rate values for different sizes of rock mass of Masino area**

This program can be used to simulate the water flow using near-field and far-field DFN models. The prepared program was run on the rock mass of the Mazino region as a large-scale model. The results showed that there were no gas leakage to the surface in the region and its coal layers were suitable for the UCG implementation. If the joint volume intensity is 50% higher than the surveyed values from the region, gases from the UCG process will leak into the earth surface, with an estimated average value of 212 liters per second. Preparation of the hydraulic DFN model for the Mazino region as a case study indicated that the proposed method and the developed computer program had the potential to be used for most of engineering problems.

## REFERENCES

- [1] Noroozi, M., Jalali, S. E., Kakaie, R. (2016). Three-dimensional geometrical simulation of rock mass discontinuities network in the access tunnel of Rudbar Lorestan dam & hydropower plant. *Tunneling and Underground Space Engineering (TUSE)*, 4(1), 53-68. (In Persian).
- [2] Noroozi, M. (2014). Estimation of Rock Mass Strength with Non-Persistence Joints using 3-D Stochastic Discrete Fractures Network (DFN) (Case Study: Rudbar Lorestan Dam & Hydropower Plant). PhD Thesis, Shahrood University of Technology, (In Persian).
- [3] Lee, I. H., Ni, C. F. (2015). Fracture-based modeling of complex flow and CO<sub>2</sub> migration in three-dimensional fractured rocks. *Computers & Geosciences* 81, 64–77.
- [4] Noroozi, M., Kakaie, R., Jalali, S.E. (2015). Three-dimensional stochastic rock fractures modeling related to strike-slip faults. *Journal of Mining and Environment*, 6(2), 169-181.
- [5] Noroozi, M., Kakaie, R., Jalali, S.E. (2015). 3D Geometrical-Stochastic Modeling of Rock mass Joint Networks (Case Study: the Right Bank of Rudbar Lorestan Dam Plant). *Journal of Geology and Mining Research*, 7(1), 1-10. doi: 10.5897/IJGMR14.0213.
- [6] Cacas, M. C., Ledoux, E., de Marsily, G. (1990). Modeling fracture flow with a stochastic discrete fracture network: calibration and validation 1. The flow model. *Water Resour. Res.* 26 (3), 479–489.
- [7] Mustapha, H. (2011). Finite element mesh for complex flow simulation. *Finite Elements in Analysis and Design*, 47 (4), 434–442.
- [8] Bodin, J., Porel, G., Delay, F., Ubertosi, F., Bernard, S. (2007). Simulation and analysis of solute transport in 2D fracture/pipe networks: The SOLFRAC program. *Journal of Contaminant Hydrology* 89, 1-28.
- [9] Zhang, Q. H., Yin, J. M. (2014). Solution of two key issues in arbitrary

- three-dimensional discrete fracture network flow models. *Journal of Hydrology* 514, 281–296.
- [10] Zhao, Z., Jing, L., Neretnieks, I. (2011). Numerical modeling of stress effects on solute transport in fractured rocks. *Comput. Geotech.*, 38(2), 113–126.
- [11] Baghbanan, A., Jing, L. (2007). Hydraulic properties of fracture rock masses with correlated fracture length and aperture. *Int. J. Rock Mech. Min. Sci.*, 44(5), 704–719.
- [12] Liu, R., Jiang, Y., Li, B., Wang, X. (2015). A fractal model for characterizing fluid flow in fractured rock masses based on randomly distributed rock fracture networks. *Computers and Geotechnics* 65, 45–55.
- [13] Long, J. C. S., Remer, J. S., Wilson, C. R., Witherspoon, P. A. (1982). Porous media equivalents for networks of discontinuous fractures. *Water Resource, Res.* 18, 645–658.
- [14] Ito, K., Seol, Y. (2003). A 3-dimensional discrete fracture generator to examine fracture-matrix interaction using TOUGH2. *TOUGH Symposium*.
- [15] Iding, M., Ringrose, Ph. (2008). Evaluating the impact of fractures on the long-term performance of the In Salah CO<sub>2</sub> storage site. *Energy Procedia* 1, 2021–2028.
- [16] Bang, S. H., Jeon, S., Kwon, S. (2012). Modeling the hydraulic characteristics of a fractured rock mass with correlated fracture length and aperture: application in the underground research tunnel at Kaeri. *Nuclear Engineering and Technology* 44(6).
- [17] Javadi, M., Sharifzadeh, M. (2012). Near Field Fluid Flow Modeling in Discontinues Fractured Media, National Conference on Water Flow and Pollution, University of Tehran, (In Persian).
- [18] Bigi, S., Battaglia, M., Alemanni, A., Lombardi, S. (2013). CO<sub>2</sub> flow through a fractured rock volume: Insights from field data, 3D fractures representation and fluid flow modeling. *International Journal of Greenhouse Gas Control* 18, 183–199.
- [19] Li, S. C., Xu, Z. H., Ma, G.W. (2014). A Graph-theoretic Pipe Network Method for water flow simulation in discrete fracture networks: GPNM. *Tunnelling and Underground Space Technology* 42, 247–263.
- [20] Xu, C., Fidelibus, C., Dowd, P. A. (2014). Realistic pipe models for flow modelling in Discrete Fracture Networks. *International Discrete Fracture Network Engineering Conference*, Vancouver, Canada.
- [21] Hyman, J. D., Karra, S., Makedonska, N., Gable, C. W. (2015). DFNWORKS: A discrete fracture network framework for modeling subsurface flow and transport. *Computers & Geosciences* 84, 10–19.
- [22] Huang, N., Jiang, Y., Li, B., Liu, R. (2016). A numerical method for simulating fluid flow through 3-D fracture networks, *Journal of Natural Gas Science and Engineering* 33, 1271–1281.
- [23] Ren, F., Ma, G., Wang, Y., Fan, L., Zhua, H. (2017). Two-phase flow pipe network method for simulation of CO<sub>2</sub> sequestration in fractured saline aquifers, *International Journal of Rock Mechanics & Mining Sciences* 98, 39–53.
- [24] Alghalandis, Y. F. (2017). ADFNE: Open source software for discrete fracture network engineering, two and three dimensional applications. *Computers & Geosciences* 102, 1–11.
- [25] Najafi, M., Jalali, S. E., Kakaie, R. (2014). Thermal–mechanical–numerical analysis of stress distribution in the vicinity of underground coal gasification (UCG) panels. *International Journal of Coal Geology* 134, 1–16.