

SPECIAL ISSUE:

Discrete Fracture Network (DFN) Modeling in Rock Mechanics

In this issue

- 1 Preface: DFN
- 3 Beginner's Guide to DFN
- 9 Applications of DFN Modeling
- 16 Permeability of Fractured Rock
- 19 Bridging the Gap
- 23 ARMA News Briefs

ARMA E-NEWSLETTER

Edited and published by

ARMA PUBLICATIONS COMMITTEE

Bezalel Haimson, Chairman

Ahmed Abou-Sayed

Amit Ghosh

Haiying Huang

Moo Lee

Gang Li

Hamid Nazari

Azra N. Tutuncu

Joe Wang

Shunde Yin

Jincai Zhang

Assistant Editors

Peter Smeallie, ARMA

Jim Roberts, ARMA

Layout Designer

Craig Keith

Editor's Note

The present Special Issue of the ARMA e-Newsletter is dedicated to Discrete Fracture Network Modeling in Rock Mechanics, the use of which has become an important tool in hydrocarbon extraction applications, as well as in mining and civil works design.

Eight leading practitioners of DFN modeling accepted our invitation and submitted articles in the form of technical notes or case histories. They will be published in two volumes, one in this newsletter, and the other in the upcoming Spring issue. ARMA member, Dr. Paul La Pointe, played a major role in securing the contributions you are invited to read. In addition to submitting a co-authored article, he also composed the Preface to this Special Issue.

Bezalel Haimson

Special Issue on Discrete Fracture Network (DFN) Modeling - PREFACE

Submitted by Paul La Pointe, Golder Associates Inc.

Discrete Fracture Network (DFN) modeling grew out of attempts by early researchers in the 1970's and 1980's to develop a technology to characterize and model the flow and transport in natural fractures for the emerging high level nuclear waste repository studies in the U.S. and Sweden. This was coupled with efforts to improve site characterization and the prediction of rock mass deformability and strength for geotechnical and civil engineering projects. Academic research in Rock Mechanics research groups during this period in the U.S. and Europe hastened the development of the technology. Advances in computer power, both graphical and computational, were essential to the growth of this field in the 1990's.

Although much early work was done to support high-level nuclear waste repository performance assessment, the usefulness of DFN modeling became readily apparent to engineers and geologists working in the mining, oil & gas, civil engineering, and groundwater protection/remediation areas, where the use has greatly increased over the past 20 years. There are now

(continued on page 2)

several commercial vendors of DFN codes, and the use of DFN models has become part of the standard workflow in many areas of rock engineering.

The articles featured in this (Winter, 2017) and a subsequent (Spring, 2017) issue of the *ARMA e-Newsletter* are intended to provide an overview of DFN modeling for those who may be less familiar with the technology, and to illustrate how DFN technology can be applied to solve many common rock engineering challenges. The information contained in these articles is by no means a comprehensive introduction to DFN modeling, nor does it exhaust the wide range of applications that have helped to meet the challenges faced by engineers in mining, oil & gas development, nuclear waste isolation, and other applications. These contributions by many of the pioneers in the field should provide an understanding of what DFN modeling entails, what sort of data is typically of use, and ways in which DFN modeling has impacted rock mechanics practice.

The articles contained in this issue focus on providing an overview of what DFN models are, the types of data that they use, key algorithmic aspects of the modeling process, and workflow elements. The articles in the second *e-Newsletter* will present applica-

tions in a number of different areas. While they do provide information on the data that is required and some general information concerning DFN modeling, their focus is on solving real-world rock engineering challenges. The articles planned for publication in the Spring issue of this newsletter are:

Marc Elmoultie: *DFN based analysis for mining: example applications and recommendations*

Paul La Pointe, Mark Cottrell, Cliff Knitter, and William Dershowitz: *Effect of Natural Fracture System on Reservoir Stimulation*

Seth Buseti, Bob Krantz, and Thomas Flottmann: *Geomechanical and Discrete Fracture Network Modeling of Coals in the Surat Basin, Australia*

Bibhuti B. Panda: *The Challenge of Modeling Groundwater Flow in Fractured Bedrock Aquifers*

Those wishing more information on DFN modeling, whether in theory or practice, should plan to attend and contribute to the ARMA-sponsored DFNE 2018 (2nd International Discrete Fracture Network Engineering Conference: <http://www.dfne2018.com/>, 20 – 22 June, 2018 in Seattle, WA, USA), which will be held in conjunction with ARMA's 2018 Annual Symposium.

An Introduction to Random Disk Discrete Fracture Network (DFN) Simulation for Civil and Mining Engineering Applications

Submitted by Matt Pierce, Itasca Consulting Group, Minneapolis

Introduction

A Discrete Fracture Network (DFN) is a three-dimensional geometric representation of joints present in a rock mass. DFNs have a wide range of uses within mining and civil engineering applications. They can be used directly in the study of structurally-defined rock blocks, such as wedges in the back of a tunnel or excavation (e.g. Grenon et al, 2016), or can be embedded within numerical models to allow for more in-depth study of rock mass strength and stability¹. For example, they can be incorporated into boundary value numerical models in order to better understand rock mass performance (e.g. around an excavation) or into Synthetic Rock Mass (SRM) samples that can be tested numerically to quantify rock mass properties such as strength, modulus, brittleness and dilation angle (e.g. Pierce et al, 2007; Mas Ivars et al, 2011). It is also possible to develop links between the geometric properties of DFNs and rock mass properties such as modulus and fragmentation (e.g. Le Goc et al., 2014; Rogers et al., 2015).

It is impossible to map the full extent of all joints present in a rock mass in three dimensions (We usually can only measure the traces where they intersect openings or ground surface.), but we can measure the orientation, fracture frequency and trace length of a subset of traces that fall along a scanline and develop statistics from these measures. It is then possible to construct a three-dimensional representation of the joints in space (a DFN) based on these statistical properties. By making a cross-section through a 3D DFN, we can produce a 2D trace map that is similar to what we see on a real 2D exposure (Figure 1). This offers a means to calibrate, or test, the DFN since we can compare real measures from scanlines to the same measures from our DFN. It is always important to test a range of DFNs for a particular rock mass domain in order to account for density variability, stochastic variability, and joint size uncertainty.

¹Caution should be used when embedding DFNs within two-dimensional numerical models, as the impact of jointing on rock mass behavior can be highly exaggerated due to the fact that out-of-plane terminations are not considered.

Random Disk DFN Modeling

There are many different models that can be used to generate DFNs, varying from simple to highly complex (see Staub et al., 2002). Although many are conceptually interesting, the majority of them have not been extensively verified for engineering applications. In addition, there is often insufficient data available to justify their use. The Baecher Disk Model (Baecher et al, 1977), commonly referred to as the Random Disk Model, and its variants are recommended as a starting point because of their simplicity and widespread availability in DFN modeling software (e.g. Fracman) and other rock mechanics software (e.g. the Itasca suite of codes.)

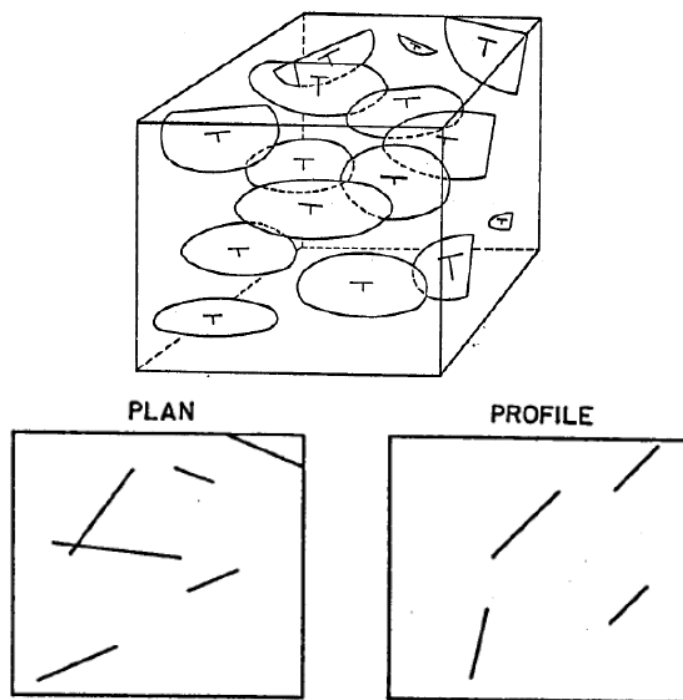


Figure 1: Random Disk DFN in which joints are represented as a collection of disks in space. Bottom: 2D trace maps can be developed by cutting through the 3D DFN and comparing to real trace maps (Baecher et al., 1977).

The fundamental assumptions of the original Baecher Disk Model are:

1. Joints are circular two-dimensional disks.

2. The center points of joints are randomly and independently distributed in space, forming a Poisson field.
3. The radii of joints are lognormally distributed².
4. Joint radius and dip are uncorrelated (statistically independent).
5. Joint radius and spatial location are uncorrelated (statistically independent).

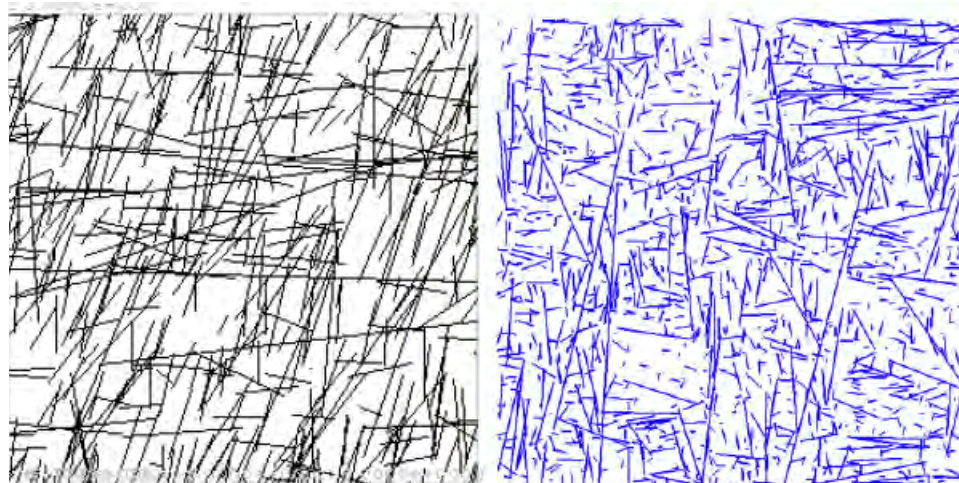
One of the main limitations of random disk DFNs is that the resulting joints exhibit X-Type intersections (i.e. they cross one another) but not T-Type intersections (i.e. where one joint terminates on another). Figure 4 is an example of a rock mass that exhibits many T-Type intersections, for which a random disk approach may not be suitable. Another example would be rock masses of sedimentary origin, since these typically exhibit very persistent sub-parallel bedding planes that are not disk-shaped, with cross-cutting joint planes that often form T-Type intersections with the bedding planes. In these cases, one can consider using a more sophisticated DFN model that considers the physics of the fracture formation explicitly in the generation process (e.g. the UFM approach, Davy et al., 2010). These have the potential to represent joint patterns more realistically (see Figure 2) and should be considered for use in cases where joint hierarchy and the associated joint terminations and intersections are expected to have a significant impact on rock mass performance.

The process of generating a random disk model is fairly simple, as outlined in the steps following, based on a tunnel example in which scanline mapping is used to gather the required data. (In reality there are a number of additional things to consider, which are discussed separately in this article.)

1. Obtain the following measurements for each joint that crosses a scanline along the tunnel wall (as illustrated in Figure 3): dip, dip direction, trace length and termination of each trace tip (on another joint, in the rock or at the edge of the mapping area).
2. Calculate the fracture frequency as the number of joints intersected divided by scanline length.
3. Make an assumption about the joint size distribution. A power law distribution with a lower cutoff of 0.5m diameter and an exponent of -4 is a good place to start (lots of small disks, a few big ones).
4. Define a box for generating the DFN (called the Generation Volume). This box should be much larger than the volume of interest (the Study Volume) in order to minimize edge effects in the generation process. The Generation Volume will be trimmed to the Study Volume prior to use.
5. Pick a random point inside the box. This is the center of a joint. Assign an orientation randomly from your list of joint orientations. Assign a joint diameter randomly from the joint size distribution you have assumed. You've now added a single joint.
6. Imagine a drift and scanline running through your box that has the same size and orientation as the real drift and scanline. Calculate the fracture frequency along this imaginary scanline. How does it compare to the real fracture frequency? If it is too low, loop back to the previous step and add more joints. If it is close to reality, move to the next step.

²A power law distribution of sizes is often also assumed.

Figure 2: Examples of trace maps generated from two different 3D DFNs. Left: DFN generated using a random disk approach, in which joints are not correlated spatially and cross one another (X-Type intersections). Right: DFN generated using a UFM approach, in which the mechanics of fracture nucleation, growth and termination is considered.



7. Calculate the trace length distribution for the imaginary drift and scanline (measure joint traces tip-to-tip whether they terminate on another joint, in the rock or at the edge of the imaginary drift wall). How does the trace length distribution compare to reality? If there are too many large traces, start over by going back to Step 3 and adjusting the exponent in your power law closer to -5. If there are too many small traces, start over by going back to Step 3 and adjusting the exponent in your power law closer to -3. If the trace lengths are a good match, you are finished.

Data Requirements, Collection and Treatment

Joint mapping often revolves around the establishment of joint sets and their associated spacing and orientation through a combination of core logging, window mapping and/or cell mapping. While joint sets remain a useful concept for characterizing jointing, information on joint size (as quantified by trace length) and joint termination is often not collected. In addition, random joints often get left out in the process of defining joint sets. Since many orebodies have a significant number of random joints, this could be important. A more detailed method of joint mapping involves the collection of explicit trace data (called discrete data). This generally involves recording the position, orientation, length and termination of a subset of traces that cross a scanline (Figure 3) but in certain cases could involve the recording of all traces within a mapping window (Figure 4). This more detailed and discrete approach to joint characterization is appealing because it lends itself to a more rigorous statistical treatment of the collected data. Any trace lengths collected are a measure of joint size,

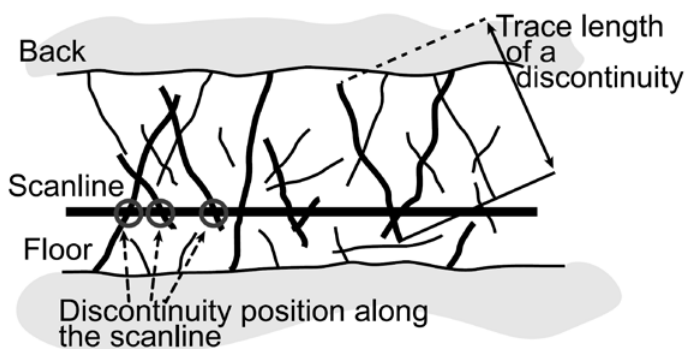
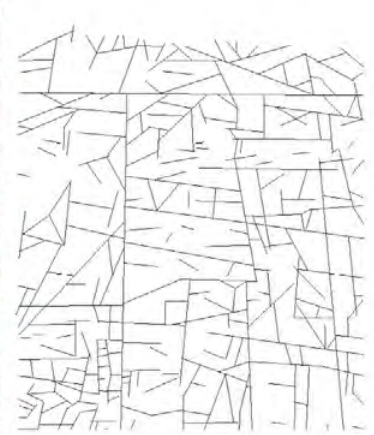


Figure 3: Sketch of a scanline in which position, trace length, orientation and termination (one, both or no ends visible) of joints can be recorded (Hadjigeorgiou et al., 2000)

whose role in defining pre-existing blocks within the rock mass is important. Unfortunately even in cases where there is considerable effort invested in data collection, not all available data are generally used, because many of the empirical systems in use rely on joint set descriptions. Discrete Fracture Networks offer a means to maximize the use of collected data.



Photograph of Kangaroo Point rock wall



Digitised discontinuity trace map

Figure 4: Example of a joint trace map (Harries, 2001). Construction of trace maps is not a common practice because it is very time consuming.

Hadjigeorgiou et al. (1995) is a good reference for mapping methods and discusses the trade-offs between the different techniques as a function of existing field conditions and intended use of data. Kemeny et al. (2006) provided an excellent review of digital imaging, laser-based imaging, image and stereo-vision hardware and software to characterize rock exposures and accuracy issues. These techniques offer several advantages in comparison with manual discontinuity sampling methods: (1) reduction of time and effort required for mapping; (2) limited exposure of operators to potentially unsafe conditions; (3) development of a permanent geomechanical database that can be consulted at any time, for example, after excavation or lining of the exposures; and (4) greater quantity of collected data, resulting in more representative and accurate values of fracture network properties.

As outlined in the previous section, we need statistical distributions of the following to make a random disk DFN: joint orientation, joint density and joint size. The following subsections discuss the collection and treatment of data that are typically used to constrain these quantities.

• Joint Orientation

Joint orientations are generally the easiest of the three main inputs to measure (in boreholes or along scanlines) and analyze (e.g. using DIPs). Rather than pick joint sets, it is recommended to use the entire range of mapped orientations as input to the DFN generation process. This is called "bootstrapping" and is available in most DFN simulation codes. The scanline/drillhole orientation also introduces a measurement bias that should be accounted for before using the data for DFN generation. A simple Terzaghi weighting of the data can be performed.

• Joint Density

Joint density is typically quantified via borehole or scanline fracture frequency counts (i.e. number of open joints per meter) using a fixed interval, generally on the order of 2-5 meters. The fracture frequency data should then be analyzed statistically to determine the lower quartile, median and upper quartile values. Separate DFNs should be constructed for each of these joint density levels. Dershowitz and Herda (1992) proposed a system for describing joint intensity based on the dimension of the sampling region (0=point, 1=linear, 2=areal, 3=volumetric) and the dimension of the feature (see Table 1). In this

context, P is followed by subscripts that refer to the dimension of the sampling region and the dimension of the feature respectively. It follows that P_{10} is the same as fracture frequency (fracture count per unit length along a scanline). The only other quantity that might be measured directly during mapping is P_{21} , which is a measure of all trace lengths within a given area. The remaining quantities are typically calculated from the DFN rather than measured.

• Joint Size

Joint size distribution is typically quantified via joint trace length. Trace lengths can only be collected from rock mass exposures. A scanline is normally made, and for each trace crossing the scanline one records the trace length and truncation (one end visible? both ends visible? no ends visible?). A statistical distribution should be fit to the trace length data for comparison to the simulated trace lengths. If actual trace lengths are not available but ends visible data have been recorded, then fracture frequency can be calculated for each category (one, two or no ends visible) and used to test the DFN. Figure 5 is an example of this. The trace length data should also be compared against the orientation data to check if there is a correlation, e.g. one particular orientation

of joints may be larger or smaller than the rest. It is important to recognize this so that they can be treated separately in the DFN construction process. When using a random disk model, it is recommended that a separate DFN be constructed for this set of joints, which can then be superimposed on the DFN generated for the remaining joints. In some cases, a more sophisticated DFN modeling approach may be warranted as discussed in the introduction.

• Reducing Sampling Bias

It is advantageous to have measures from multiple scanlines and/or boreholes of varying orientation, especially if there is a preferred joint orientation. This means mapping

Table 1: System for describing joint density and intensity. (Dershowitz and Herda, 1992)

		0	1	2	3	
Dimension of Sampling Region	0	P_{00} Length⁰ Number of Fracture Samples per Point Sample of Rock Mass				◀ ◀ POINT MEASURES
	1	P_{10} Length⁻¹ Number of Fractures per Unit Length of Scanline (Frequency or Linear Intensity)	P_{11} Length⁰ Length of Fracture Intersects per Unit Length of Scanline (Linear Porosity)			◀ ◀ LINEAR MEASURES
	2	P_{20} Length⁻² Number of Trace Centers per Unit Sampling Area (Areal or Trace Density)	P_{21} Length⁻¹ Length of Fracture Traces per Unit Sampling Area (Areal or Trace Intensity)	P_{22} Length⁰ Area of Fractures per Unit Sampling Area (Areal Porosity)		◀ ◀ AREAL MEASURES
	3	P_{30} Length⁻³ Number of Fracture Centers per Unit Rock Volume (Volumetric Density)	P_{31} Length⁻¹ Area of Fractures per Unit Volume of Rock Mass (Volumetric Intensity)	P_{32} Length⁻¹ Volume of Fractures per Unit Volume of Rock Mass (Fracture Porosity)	P_{33} Length⁰	◀ ◀ VOLUMETRIC MEASURES
		DENSITY		INTENSITY		POROSITY

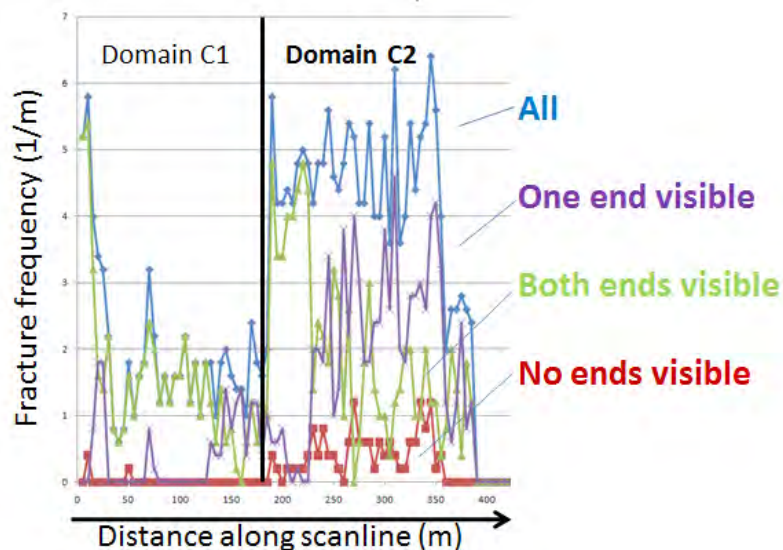


Figure 5: Example of scanline mapping data from a tunnel demonstrating how fracture frequency measures can be made on the basis of how visible the trace ends are. This can be used to constrain joint size in the DFN construction process (e.g. where trace length data is not available)

endwall and back exposures in addition to sidewall exposures in both directions (where possible) within tunnels and drilling in more than one orientation. It will not always be possible to match the fracture frequency on all of these at the same time but the DFN should at least reflect any anisotropy present (e.g. if the vertical scanline frequency is double the horizontal in reality, the DFN scanline fracture frequency should at least come close to this ratio. If not, there is probably something wrong with the joint orientation input).

• Data Quantity

Most statistical techniques defining the structural fabric of a rock mass are only applicable when a sufficient amount of data is available. This can be a challenge in deep and high stress mines. There is often a scarcity of quality data due to mapping difficulties such as limited access, coverage of wall exposures with shotcrete or wire-mesh, dust, poor lighting and noise. These adverse conditions are often compounded by the need to comply with strict production constraints.

Statistical tests (e.g. Kolmogorov–Smirnov) can be used to establish whether there is sufficient statistical agreement between field data and simulated data. In most cases, however, it will not be possible to generate a single DFN that is representative of the entire mine. Rather, one must develop a series of DFNs to reflect joint variability (e.g. differences in fracture frequency) as well as uncertainty in joint size (most common) or orientation (less common),

even within a single domain. As a result, the required amount of data is mostly a function of how variable the rock mass is.

It is recommended that a number of scanlines be mapped that offer good coverage across the orebody and also are of differing orientation. In general, each scanline should contain a minimum of 100 trace measurements (with orientation, position, length and/or termination recorded for each trace crossed). This should highlight differences among regions and provide a starting point for establishing statistics for generating DFNs for different domains. In the process, it will likely become clear that there is insufficient data in specific domains or relating to specific data (e.g. trace length), which should provide focus for further data collection via drilling (e.g. to get orientation and fracture frequency data) and/or scanline mapping.

Accounting for Uncertainty and Variability

Uncertainty could arise from poor or sparse drilling or mapping coverage and could be associated with orientation, density and/or size distribution of the joints. A series of DFNs should be made by varying the inputs for which there is uncertainty. These are carried forward into analyses so that the impact of this uncertainty on the project can be quantified. As the project advances and additional data becomes available, the range of likely DFNs can be narrowed and the associated drop in project uncertainty quantified.

The first step in handling variability is to break the rock mass up into geotechnical domains. Most of the rock within a given domain would be expected to exhibit similar joint patterns and these can normally be identified via spatial analysis of the orientation, fracture frequency and trace length data. There is typically a limit to how many domains the rock mass can be subdivided into (based on drilling coverage) and so fracture frequency is still likely to vary significantly even within a single domain. One should aim to quantify the lower quartile, media and upper quartile (25th, 50th and 75th percentiles) fracture frequencies within each domain so that a series of DFNs representing the range in joint density can be developed. In most cases, a single set of orientations and trace lengths can be considered for each domain.

In general, several sets of DFNs should be produced to reflect the variability in joint density (DFNs calibrated to different fracture frequencies, e.g. lower, median and upper quartile) and the uncertainty in joint size (DFNs generated using different assump-

tions about the power law exponent, particularly when no trace length data is available).

Since DFN simulation involves sampling randomly from a set of input distributions (stochastic process), one will get a different outcome each time the process is repeated. Each outcome (from a given set of inputs) is called a realization. It is important to note that while each realization will look different, each represents an equiprobable outcome from the inputs and (if done correctly) will honor the input data. So, for each set of inputs (e.g. for a particular combination of orientation, density and size distribution) it is common practice to generate several DFN realizations in order to account for stochastic variability.

Assuming we want to test three different joint densities (lower, median and upper quartile fracture frequency) and three different joint size distributions, we will have $3 \times 3 = 9$ different sets of inputs. If three realizations are generated per set of inputs (probably a bare minimum), one would end up generating 27 DFNs per domain. By carrying all of these through to analyses, one can generate a probability distribution for the prediction (fragmentation, strength, etc.) that reflects the combined effects of density variability, stochastic variability and joint size uncertainty that can be fed into risk-based evaluations of rock mass performance.

Conclusions

Random Disk Modeling can be used to generate Discrete Fracture Networks for a particular rock mass as an aid to thought or for the study of excavation performance and rock mass properties. The purpose of the article was to outline the basics of Random Disk Modeling (for those new to the method) and to outline some basic considerations for data collection, accounting for rock mass variability and uncertainty in mining and civil engineering applications. The limitations of the approach were also discussed and some examples provided where more sophisticated approaches may be warranted.

References

- Baecher G.B., N.A. Lanney, H.H. Einstein (1977). Statistical Description of Rock Properties and Sampling. Proceedings of the 18th U.S. Symposium on Rock Mechanics, 5C1-8.
- Davy, P., R. Le Goc, C. Darcel, O. Bour, J. R. de Dreuzy and R. Munier. (2010). A Likely-Universal Model of Fracture Scaling and its consequence for crustal hydro-mechanics. Journal of Geophysical Research - Solid Earth.
- Dershowitz, W.S.; Herda, H. (1992), "Interpretation of Fracture Spacing and Intensity," Proc. 33rd. U.S. Symp. on Rock Mechanics, Balkema.
- Grenon, M, A. Landry, J. Hadjigeorgiou & P. Luc Lajoie (2016): Discrete fracture network based drift stability at the Éléonore mine, Mining Technology, DOI: 10.1080/14749009.2016.1199296
- Hadjigeorgiou J., Lessard, J. F., Villaescusa, E. and Germain, P. (1995). An appraisal of structural mapping techniques. Second International Conference on Mechanics of Jointed and Faulted Rock, Vienna Balkema, 191–198.
- Hadjigeorgiou, J., Lessard, J.F., Bruneau, G., Grenon, M. (2000). Evaluation of deterministic ground support design for underground excavations. 2000 Tunnelling Association of Canada Annual Publication.
- Harries, N. J. (2001). Rock Mass Characterization for Cave Mine Engineering, Ph. D. thesis, University of Queensland.
- Kemeny, J., Turner, K. and Norton, B. (2006). LiDAR for rock mass characterization: hardware, software, accuracy and best-practices, in Proceedings of the laser and photogrammetric methods for rock face characterization workshop, (eds. F. Tonon and J. Kottenstette), 49–61, Minneapolis, MN, American Rock Mechanics Association.
- Le Goc, R., C. Darcel, P. Davy, M. Pierce and M.A. (2014). Brossault. Effective elastic properties of 3D fractured systems, in Proceedings of the First International Conference on Discrete Fracture Network Engineering, Vancouver.
- Mas Ivars, D., Pierce, M.E., Darcel, D., Montes, J.R., Potyondy, D.O., Young, R.P. and Cundall, P.A. (2011). The synthetic rock mass approach for jointed rock mass modeling. Int. J. Rock Mech. Min. Sci. 48, (2), 219-244.
- Pierce, M., P. Cundall, D. Potyondy and D. Mas Ivars. "A Synthetic Rock Mass Model for Jointed Rock," in Rock Mechanics: Meeting Society's Challenges and Demands (1st Canada-U.S. Rock Mechanics Symposium, Vancouver, May 2007), Vol. 1: Fundamentals, New Technologies & New Ideas, pp. 341-349. E. Eberhardt et al., Ed. London: Taylor & Francis Group, 2007.
- Rogers, S., D. Elmo, G. Webb and A. Catalan. Volumetric Fracture Intensity Measurement for Improved Rock Mass Characterization and Fragmentation Assessment in Block Caving Operations. Rock Mechanics and Rock Engineering, DOI 10.1007/s00603-014-0592-y.
- Staub, I., Fredriksson, A. and Outters, N. (2002). Strategy for a rock mechanics site descriptive model development and testing of the theoretical approach, SKB report, No. R-02-02, prepared for

Rock Engineering Applications of Discrete Fracture Network Modeling

Submitted by Davide Elmo, NBK Institute of Mining Engineering, University of British Columbia, Vancouver, Canada

This paper describes recent advances in Discrete Fracture Network (DFN) modeling and analysis. These advances demonstrate that DFN modeling plays a key role in the studies of the mechanical behavior of fractured rock masses. This paper provides examples of two applications of DFN modeling in the field of rock engineering: (1) synthetic rock mass modeling of rock mass strength and scale effects; and (2) analysis of slope stability and step-path failure.

Introduction

Discrete Fracture Network (DFN) modeling is increasingly being used to help provide solutions for many geotechnical and mining engineering problems. Paraphrasing Dershowitz et al. (2004), the DFN approach can be defined as the analysis and modeling process that explicitly incorporates the geometry and properties of discrete fractures as a central component controlling rock mass behavior. Using probability density functions to represent the properties of natural fractures, the DFN represents an ideal numerical tool to synthesize realistic fracture network models from digitally and conventionally mapped fracture data (Figure 1). Within the practical and operational constraints imposed by active engineering projects, geotechnical and rock mechanics engineers should be aware of the level of data characterization and steps required to generate a realistic DFN model.

From Data Collection to DFN Models for Rock Engineering Applications

It is well understood that the value of a DFN model depends directly on the quality and quantity of available field data. However, in the author's opinion, practitioners and researchers tend to overlook the fundamental relationship between the data collection process and the generation of DFN models for rock engineering applications. In general terms, the generation of a DFN model requires collecting

information on: (1) fracture orientation; (2) fracture intensity; (3) fracture length; and (4) fracture terminations. (see Figure 2.) The data collection process should be driven by the knowledge of the limitations that are inherently introduced into the analysis by the sampling method being adopted (For example, Elmo et al., 2015, 2016):

- The randomness of natural geological processes is responsible for the manifested variability of the parameters used as input in DFN models. Data variability can be defined as the observable manifestation of heterogeneity of physical parameters, and should not be confused with data uncertainty (state of knowledge, required to describe the observed variability in a qualitative or quantitative manner). The adopted field mapping approach should aim at minimizing data uncertainty and capturing data variability.
- Fracture length is an important parameter for DFN modeling. However, this parameter is either seldom available due to a lack of exposures, or engineers have limited access to length data collected along exploratory drifts. Censoring and truncation bias need to be carefully considered when collecting fracture length data.

Ubiquitous Fracture Model		Discrete Fracture Network Model
Fracture occurrence often ubiquitous		Fractures are not ubiquitous but governed by an underlying spatial model
Fractures are considered infinite in length		Fractures have variable lengths
Fracture sets having non geological orientation distributions		Fracture sets have variable orientation
Fractures independent of each other		Real fractures are not independent (e.g. fractures can terminate on each other)

Figure 1: The DFN approach allows one to consider fracture properties in a more realistic manner compared to the more conventional Ubiquitous Fracture Model.

- The stochastic nature of the DFN process is such that there are an infinite number of possible realizations of the fracture system based on the mapped data. This translates to an additional layer of data variability (e.g. variability of rock mass strength) once the DFN model is embedded within geomechanical models (Elmoultie and Poropat 2011).

As shown in Figure 2, DFN models are subjected to a process of data calibration and validation. For example, fracture intensity targets can be calibrated by taking the boreholes with their identified P10 intervals and testing the DFN model to identify how many fractures intersect those P10 intervals. Calibration of fracture orientation data set is similar to the intensity tests, with the orientation of fractures intersected by

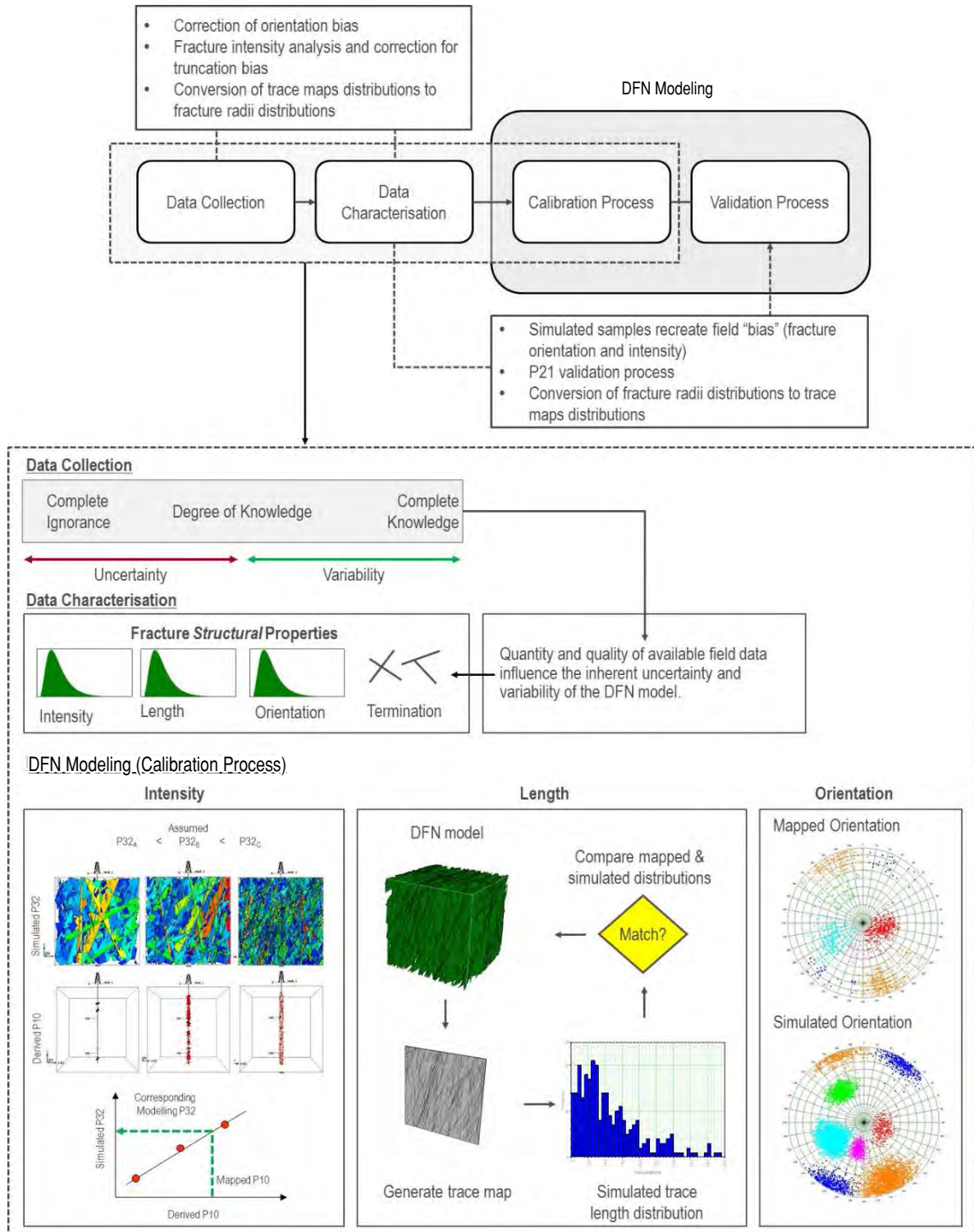


Figure 2: Processes of data collection, data characterization, and DFN model calibration and validation for rock engineering applications.

the boreholes/surface exposures in the model compared against the fractures mapped in the field. Calibration of fracture length data can be performed by comparing the distribution of simulated trace maps to the distribution of mapped trace maps in the field.

For mine scale DFN models, a significant degree of model calibration may be required as the modeling volume, and its internal variability, may be much greater than for small scale DFN models. Even though the calibration process used to generate a DFN model would arguably guarantee that the DFN model is producing results within specified limits by comparison with the field data used to define the input parameters, the process does not provide a guarantee of validation. For a DFN model to be validated, simulated samples should recreate the sampling bias associated with the data collection process. If available, areal intensities (P21) could be used to validate a DFN model, as typically only linear intensities (P10) are used to provide targets volumetric intensities (P32) and calibrate fracture intensity data. By comparing simulated and mapped P21 values the validation process would be based on an independent target value not used to generate the DFN model.

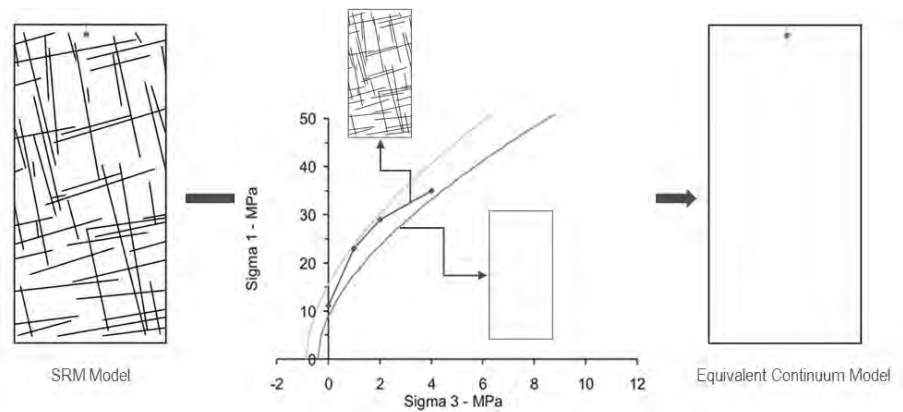


Figure 3: Use of SRM modeling to define equivalent continuum failure envelopes (modified from Elmo et al., 2016)

ties for a portion of the rock mass up to the representative elementary volume (REV), Figure 3. DFN modeling lies at the core of the SRM approach, as it recognizes that at every scale rock mass behavior may be dominated by a limited number of discrete fractures. The use of SRM modeling allows for the definition of equivalent Mohr-Coulomb and/or Hoek-Brown strength envelopes, with better consideration for rock mass behavior at relatively low confinement. The reliability of the SRM results is clearly related to the uncertainty and variability characteristics of the underlying DFN models used in the simulations. Furthermore, the stochastic nature of DFN modeling indirectly makes the SRM analysis a stochastic approach on its own, which has clear implications for rock engineering design.

As discussed in Elmo (2012) and Elmo et al. (2016), it is possible to relate the jointing conditions of SRM models to the structural character of the rock mass as

DFN Modeling and Rock Engineering

• Analysis of Rock Mass Behavior

The Synthetic Rock Mass (SRM) approach can be used to define equivalent continuum rock mass proper-

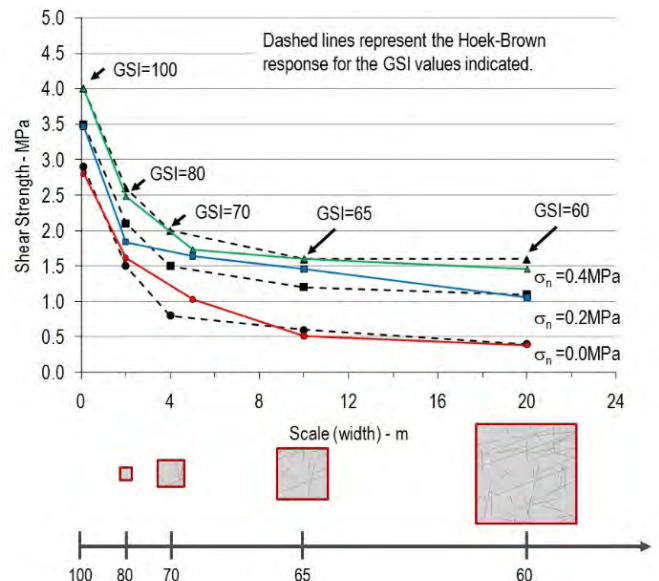
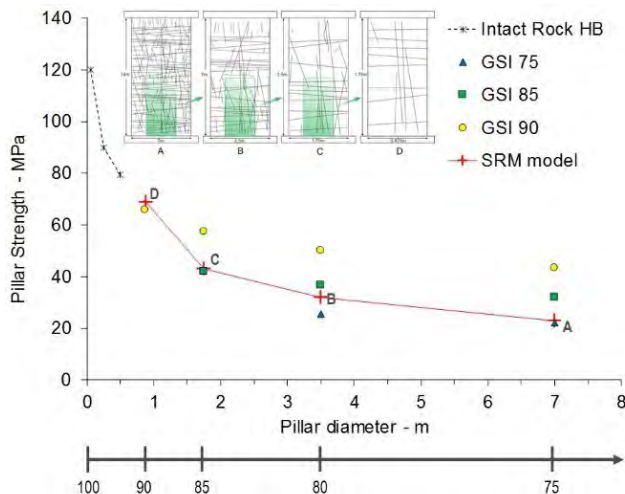


Figure 4: Strength results of SRM models (left, pillars; right, direct shear test models) at different scales and the related degree of rock mass blockiness in terms of GSI (modified from Elmo et al., 2016).

defined by the Geological Strength Index (GSI, Hoek et al., 1995). Figure 4 shows the strength results obtained for SRM pillar models (width-to-height ratio of 0.5) at different scales, and the associated degree of rock mass blockiness in terms of GSI. Similarly, Figure 5 shows the correlation between SRM strengths for fractured rock masses subjected to direct shear loading conditions and estimated GSI ratings for the progressively larger SRM models. The results show that there exists a scale at which the influence of natural fractures on rock mass behavior can be “averaged” to produce an effective continuum response.

• Analysis of Step-Path Failure

Over the past 15 years several studies have been conducted that focused on using the DFN approach to address the step-path/intact rock bridge problem (e.g. Stead et al., 2004, 2007; Elmo et al., 2007, 2009, 2011; Eberhardt et al., 2004). The step-path problem considers discrete fractures that may provide discrete connections with the highest potential for failure. The task of rock engineering is to characterize those potential pathways, rather than considering the average rock mass properties of the REV within the context of limit equilibrium or finite element analysis.

Whereas it may be possible to develop simple step-path recognition algorithms to provide the likely failure path for a given synthetic rock mass, those algorithms can only incorporate basic principles of stress analysis and cannot fully consider and incorporate the fracture mechanics principles that control intact rock failure in the field. To achieve this, it is necessary to integrate the DFN approach with geomechanical codes capable of simulating brittle failure along discrete connections. In other words, the problem requires not only understanding the geometry of the discrete fractures, but also considering their shear strength properties in relation to the induced stress field.

Geomechanical codes capable of explicitly simulating brittle failure and kinematics aspect of rock mass failure are, however, computationally very intensive. Considering the stochastic variability of DFN models, simple step-path recognition algorithms could still be used to identify which critical sections should be tested in the geomechanical models, thus limiting the computational time that may be required to obtain reliable estimates of rock bridge percentage for a given step-path failure surface.

This is demonstrated in Figure 5, which shows a conceptual model for an 800m high rock slope, with embedded DFN based trace maps representing varying jointing conditions. Each model includes three main joint sets dipping at 10°L, 80°L and 80°R (Model A), and 30°L, 60°R and 80°R (Model B) respectively (the letters L and R stand for Left and Right dip direction with respect to the horizontal axis). The simulated joints in the models represent very persistent fractures according to the ISRM (1981) definition, with an average fracture a length in the range from 20m to 40m.

The mesh discretization size determines the minimum fracture length that is possible to consider in the geomechanical model without compromising computational times. The introduction of a minimum size fracture cut-off has an impact on the assumed fracture intensity in the DFN model, as the probability density function for fracture length would be bounded by a minimum value and, if appropriate, by a maximum value, but realistically is not possible to define the full extent of the distribution. Accordingly, there would be *unfractured* portions of rock mass in the model that would have some degree of fracturing in the field. To represent this fracturing, equivalent rock mass properties can be estimated using a synthetic rock mass approach (Figure 6) to define equivalent Hoek-Brown/GSI properties (Elmo et al., 2009).

Figure 7, Figure 8, and Figure 9 show the maximum

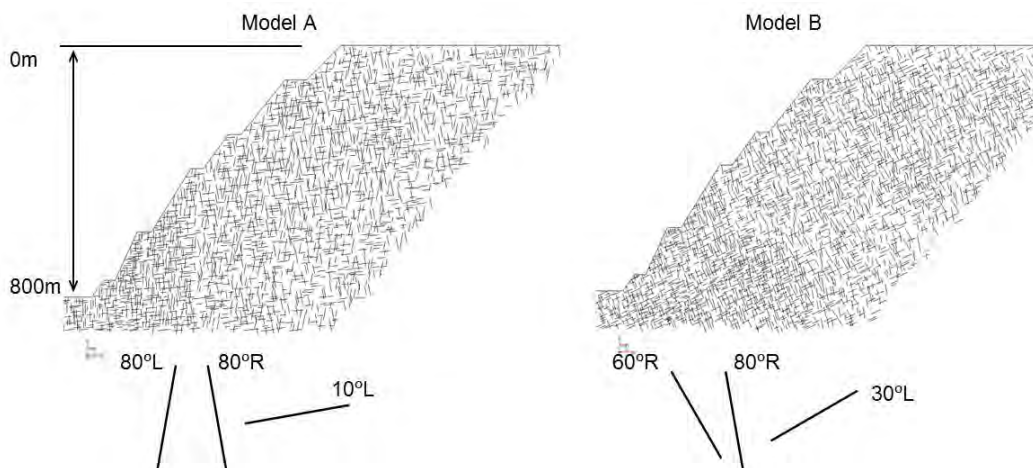


Figure 5: Conceptual model for an 800m high rock slope, with embedded DFN based trace maps representing varying jointing conditions (modified from Elmo et al., 2009).

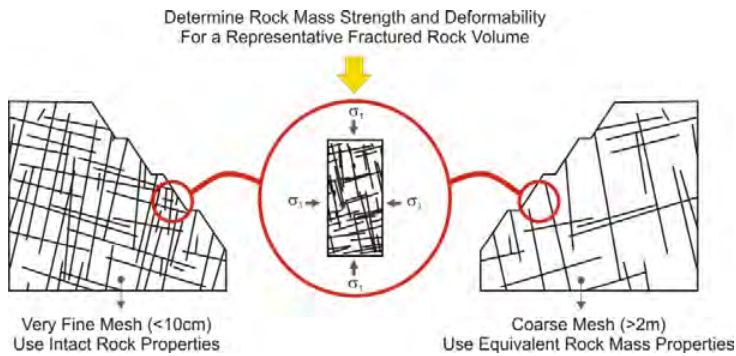


Figure 6: Synthetic rock mass approach used to define equivalent rock mass properties that account for small scale fracturing (modified from Elmo et al, 2009)

extent of step-path mechanisms and extent of horizontal displacement simulated in the models for varying rock mass properties and jointing conditions. The maximum extent of step-path failure identifies the zone within which primary and secondary brittle fracture processes have occurred, as defined by Stead et al. (2007). In the models, step-path mechanisms appear inhibited deep within the rock mass. Furthermore, the initial jointing conditions largely control these mechanisms, and do not necessarily extend from the toe of the slope up to the slope crest.

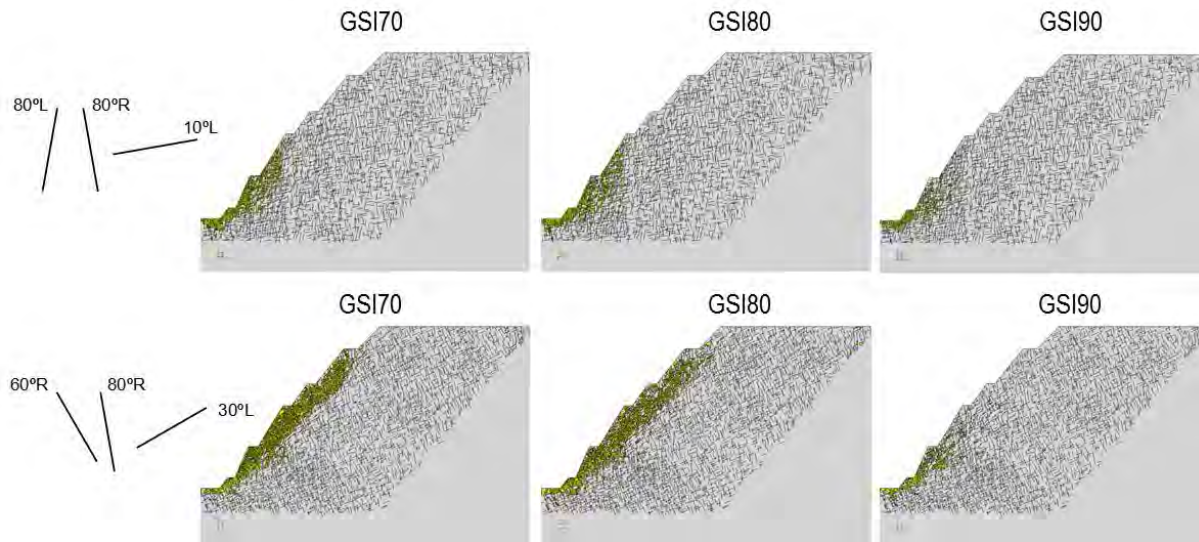


Figure 7: Areas in the slope impacted by step-path failure mechanisms (yellow areas) for varying rock mass properties and jointing conditions.

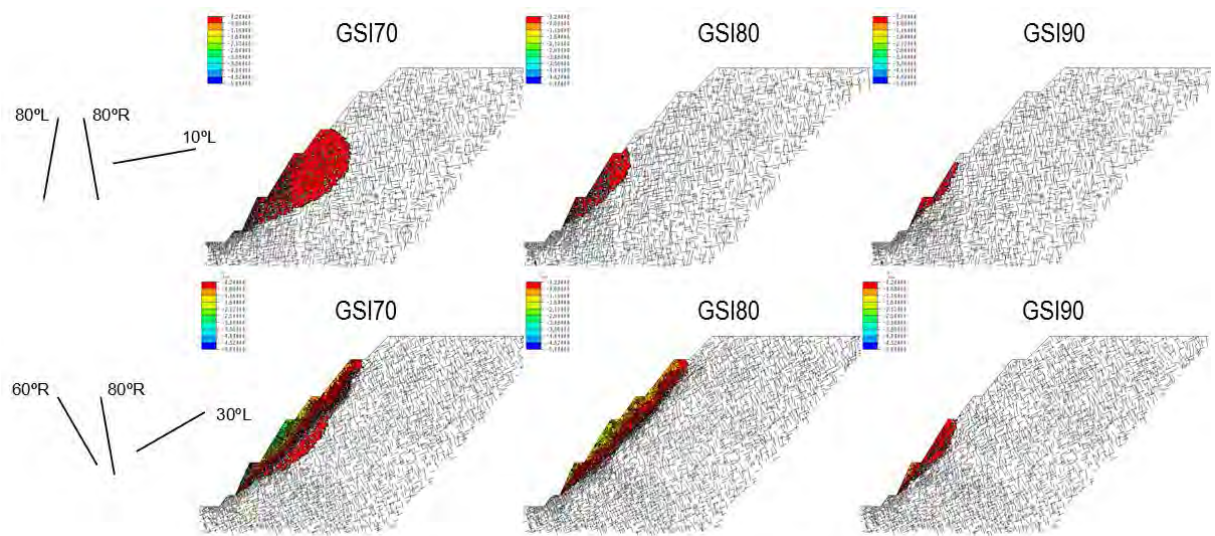


Figure 8: Extent of horizontal displacement (red contours corresponds to 0.2m) for varying rock mass properties and jointing conditions.

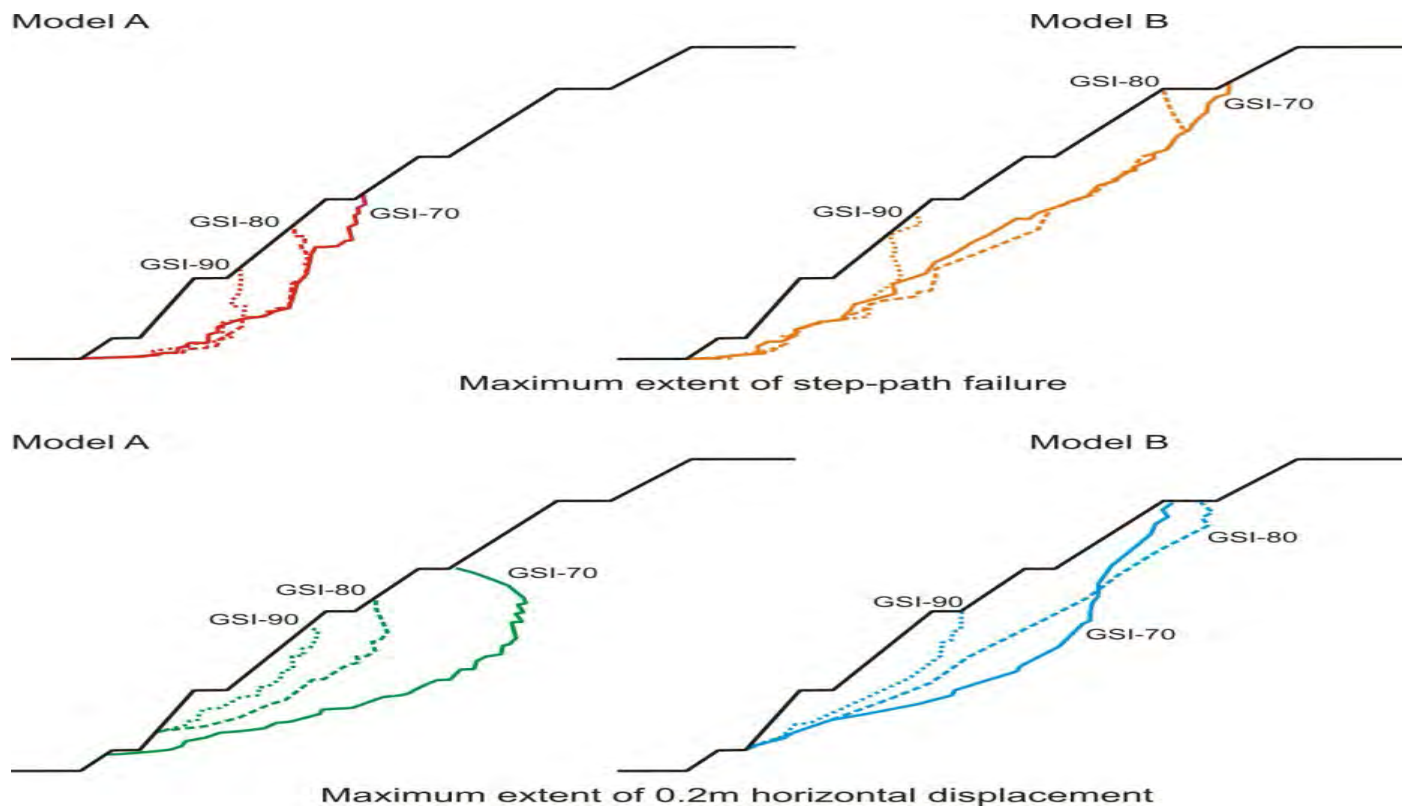


Figure 9: Maximum extent of step-path failure mechanisms and 0.2m horizontal displacements for varying rock mass properties and jointing conditions.

Conclusions

The DFN approach takes full advantage of fracture data collected from mapping of exposed surfaces and boreholes, including also digital photogrammetry and laser scanning techniques. Limitations inherently introduced by the sampling methods being adopted represent important aspects that should drive the collection of fracture data for DFN analysis. This paper has provided examples of two application of DFN modeling in the field of rock engineering: (1) synthetic rock mass modeling of rock mass strength and scale effects; and (2) analysis of slope stability and step-path failure. When integrated with geo-mechanical codes to generate SRM models, the DFN approach offers an opportunity to better analyze the concept of REV, and the reduction of rock mass strength with increasing volume up to the REV. In terms of stability analysis of rock slopes, DFN models allow for a better consideration of the role that the jointing conditions (spatial intensity, structural character, and shear strength properties) play with respect to development of step-path failure. Further modeling is required to investigate the impact that a range of stochastically generated DFN realizations may have on the maximum extent of step-path mechanisms and associated slope stability.

Acknowledgments

I would like to express my gratitude to Dr. Steve Rogers (Golder Associates, Vancouver, Canada) and Dr. Bill Dershowitz (FracMan Group, Golder Associates, Seattle). They are my true "*DFN mentors*", and over the past 13 years they taught me "*the ways of the DFN force*".

References

- Dershowitz, W.S., P. R. La Pointe & T. W. Doe. 2004. Discrete fracture network modeling: Current status and future trends. National Groundwater Association/EPA Fractured Rock Conference, Portland Maine, 13-15 Sept. 2004.
- Eberhardt, E., Stead, D., & Coggan, J.S. 2004. Numerical analysis of initiation and progressive failure in natural rock slopes-the 1991 Randa rockslide. *Int. J. Rock Mech. Min. Sci.*, 41, 69-87.
- Elmo D., D. Stead & S. Rogers. 2015. Guidelines for the quantitative description of discontinuities for use in Discrete Fracture Network Engineering. *Proceedings of the 13th ISRM Congress*. Montreal, May 10-13th. Paper 587.

- Elmo D., K. Moffitt & J. Carvalho. 2016. Synthetic rock mass modeling: experience gained and lessons learned. 50th U.S. Rock Mechanics Symposium. Houston, Texas, June 2016. Paper 777.
- Elmo D., K. Moffitt, S. D'Ambra & D. Stead. 2009. A quantitative characterisation of brittle rock fracture mechanisms in rock slope failures. International Symposium on Rock Slope Stability in Open Pit Mining and Civil Engineering, Santiago, Chile.
- Elmo, D. 2012. FDEM & DFN modeling and applications to rock engineering problems. MIR 2012 - XIV Ciclo di Conferenze di Meccanica e Ingegneria delle Rocce - Nuovi metodi di indagine, monitoraggio e modellazione degli ammassi rocciosi. Faculty of Engineering, Turin University, Italy.
- Elmo, D., Yan, M., Stead, D. & Rogers, S. 2007. The importance of intact rock bridges in the stability of high rock slopes: Towards a quantitative investigation using an integrated numerical modeling - discrete fracture network approach. Proc. Int. Symp. on Rock Slope Stability in Open Pit Mining and Civil Engineering, Perth, Australia.
- Elmoultie, M.K. & Poropat, G.V. 2011. Uncertainty propagation in structural modeling. Proc. Int. Symp. on Rock Slope Stability in Open Pit Mining and Civil Engineering, Vancouver, Canada.
- Hoek, E.T., Kaiser, P.K. & Bawden, W.F. 1995. Support of underground excavations in hard rock, A.A. Balkema, Rotterdam.
- ISRM 1981. International Society Rock Mechanics suggested methods for rock characterization testing and monitoring. Brown, E T Editor Imprint Oxford: Pergamon. 211 pp.
- Stead, D., Coggan, J.S. & Eberhardt, E. 2004. Realistic simulation of rock slope failure mechanisms: the need to incorporate principles of fracture mechanics. Int. J. Rock Mech. & Min. Sci., 41.
- Stead, D., Coggan, J.S., Elmo, D. & Yan, M. 2007. Modeling brittle fracture in rock slopes: Experience gained and lessons learned. Australian Centre for Geomechanics. Int. Symp. Rock Slope Stability in Open Pit and Civil Engineering, Slope Stability07, Perth, Western Australia, September 12-14 2007, 239-252.



Join Us

51st US Rock Mechanics/Geomechanics Symposium in San Francisco

■ San Francisco 2017 Symposium

ARMA has accepted close to 800 abstracts for its 51st U.S. Rock Mechanics / Geomechanics Symposium to be held in San Francisco, California, USA on 25-28 June 2017. Five keynote talks will be given by Francois Cornet (9th Annual MTS Lecture), Derek Elsworth, David Yale, Erik Westman, and Maria-Katerina Nikolinakou. Two short courses will be offered on Shale Gas GeoEngineering by Maurice Dusseault and 2D and 3D Modeling of Rock Fracturing Processes in Geomechanics by Andrea Lisjak and Bryan Tatone. Three workshops will be offered on Emerging Advances in Geomechanics, Hydraulic Fracturing, and How Laboratory Geomechanics Testing Adds Value to Exploration and Production.

Technical tours will include visits to the Carl Zeiss X-ray Microscopy Facility, Stanford University Campus and Rock Mechanics Labs, and the SLAC National Accelerator Laboratory. Up to 20 exhibitors are expected to participate.

Special events include the annual awards dinner, a "Rock Jeopardy" contest, student career reception, major league baseball game, trips to Alcatraz, Muir Woods, Sausalito, the California Academy of Sciences, the De Young Museum, and highlights of the city. A post-symposium "bridge walk" over the Golden Gate Bridge, and a hot air balloon ride and winery visit to Napa Valley cap the special activities.

Registration and further information can be found at www.armasyposium.org.

Full Permeability Tensor of a Three-dimensional Fractured Rock Mass

Submitted by P. S. Lang (Abingdon Technology Centre, Schlumberger, Oxford, United Kingdom, and Department of Earth Science and Engineering, Imperial College, London, United Kingdom); A. Paluszny and R. W. Zimmerman (Department of Earth Science and Engineering, Imperial College, London, United Kingdom).

The macroscopic-scale permeability of fractured rock is of vital interest to various earth science and engineering disciplines, as the majority of hydrocarbon reservoirs and proposed sites for radioactive waste disposal are heavily fractured (Van Golf-Racht, 1982; Wu et al., 2002). The equivalent, or “block” permeability, quantifies the collective permeability behavior of the fractures and rock matrix. In engineering practice, hydraulic analysis of fractured rock is often reduced to a two-dimensional problem, owing to computational limitations, especially if multi-physics effects are incorporated into the model (Nick et al., 2011; Rutqvist et al., 2013). Three-dimensional flow properties are then deduced from two-dimensional calculations (Pouya and Fouche, 2009; Reeves et al., 2013). However, the reduction from three-dimensional to two-dimensional analysis of the permeability of a fractured rock mass introduces errors in both the magnitudes and directions of the principal permeabilities. This error can be numerically quantified for porous/fractured rock by comparing the equivalent permeability of three-dimensional fracture networks to the values computed on arbitrarily extracted planar trace maps.

A method to compute tensorial permeability in 3D

A new methodology to compute the full permeability tensor of three-dimensional discrete fracture and matrix models is discussed in this article. The method is based on the element-wise averaging of pressure and flux, obtained from a finite element solution to the Laplace problem, and has been validated against analytical expressions for periodic anisotropic porous media.

A series of incompressible, single-phase flow problems are solved over a porous medium domain using the finite-element method in order to determine the full equivalent permeability tensors. For each simulation, the resulting scalar pressure field is post-processed to yield a pressure gradient vector field. Element-wise constant fluxes are computed using local element pressure gradients, and permeability is computed by applying Darcy’s law. Contributions

to the equivalent permeability tensor components are a function of element-volume weighted averaging of pressure gradients and fluxes. The resulting over-constrained problem is solved using a least-squares approximation. The asymmetric effect of permeameter-type flow constraints is relaxed by excluding a peripheral region along the outer boundary from the tensor calculation.

Two- and three-dimensional periodic media models are used to validate this procedure (Lang et al., 2014). Validation problems demonstrate that even with asymmetric permeameter constraints on flow experiments, a representative tensor is accurately obtained. Advantages of this approach are numerous: full use can be made of flexible meshing techniques and geological realism of representation of heterogeneities; fractures can be represented as surfaces, relaxing the need for local mesh refinement; no assumption on the orientation of principal permeabilities are made; varying permeability in both rock matrix and permeable individual fractures is permitted; computational efficiency and simplicity is achieved, since the analysis is based on finite-element solution of a Laplace equation and subsequent mesh traversal only.

Relative errors are less than 10^{-3} for all of the verification models. Part of this error is attributed to the fact that for lower dimensional representation of fractures, no additional degrees of freedom are introduced. This results in a shortcoming in accounting for flow within the fracture perpendicular to its orientation. This brings about a 10^{-4} error in matching the harmonic mean for test cases in which flow occurs normal to a set of parallel fractures, and confirms that fractures contribute to a minor extent to overall conductivity in their normal direction.

3D vs. 2D analysis of flow through fractured rock masses

A series of cube-shaped models consisting of a discrete fracture network embedded in a porous rock matrix is created using stochastically generated fracture patterns of increasing fracture density. Hydraulic

aperture is sub-linearly correlated to fracture length (Olson, 2003). For each of the three-dimensional models, a series of seventy-five randomly oriented two-dimensional cut-planes is extracted. For isotropic networks consisting of power-law size distributed fractures with length-correlated apertures, two-dimensional cut planes are found to underestimate the magnitude of the macroscopic-scale permeability by up to three orders of magnitude near the percolation threshold, approaching an average factor of deviation of three as the fracture density increases. At low fracture densities, percolation may occur in three dimensions, but not in any of the two-dimensional cut planes. Anisotropy of the equivalent permeability tensor varies accordingly, and is more pronounced in two-dimensional extractions.

These results confirm that two-dimensional analysis cannot be directly used as an approximation of three-dimensional equivalent permeability, using standard descriptions of fracture density. Maximum and minimum principal permeabilities are underestimated by up to three orders of magnitude near the percolation threshold, and, on average, by a factor of three for higher densities. Above the percolation threshold, trace maps provide an order of magnitude accurate estimation of volumetric permeability. An alternative expression of fracture density, based on a modified definition of the 'excluded area' concept (Lang et al., 2014), can be used to approximate three-dimensional flow properties in cases where only two-dimensional analysis is available.

Length Scales and Realism

The absence of a clear separation of length scales in most fractured rock engineering problems poses a fundamental problem with respect to permeability homogenization. Rock joints have been shown to extend to maximum lengths of between hundreds and thousands of meters (Olson, 2003). This range effectively covers typical distances of externally imposed pressure gradients, such as inter-well communication in oil and gas reservoirs, and excavations in geological disposal facilities, to name two examples.

The approach presented herein retrieves the full permeability tensor for blocks of fractured porous rock without the assumption that one is working on a representative volume element of the network, and thereby separates itself from previous approaches to effective permeability computation (Koudina et al., 1998; Bogdanov et al., 2003). It has been shown that the use of border regions in the sub-sampling procedure allows representative symmetric tensors to

be retrieved, even if the physical flow constraints are asymmetric. This approach aims to improve on the diagonal-tensor characterization of fractured rock block models (Gonzalez-Garcia et al., 2000) without requiring an extension to periodic models.

The presented application to isotropic fracture networks with planar, disk-shaped joints and strict length-dependent transmissivity relationship is, of course, a simplification of a difficult and complex problem. Geologically realistic fracture networks show high anisotropy of fracture patterns and individual joint permeability (Olson, 2003), as complex functions of their displacement history and diagenetic processes. Recent advances in geomechanical models allow for the creation of such models in three dimensions (Paluszny and Zimmerman, 2013).

References

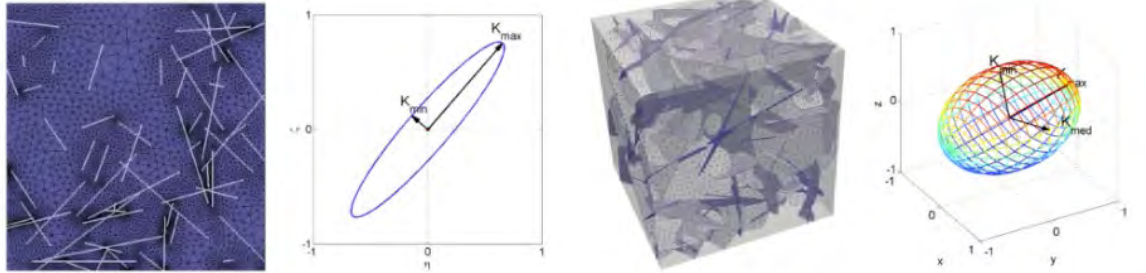
- Bogdanov, I.I., V.V. Mourzenko, J.-F. Thovert, and P.M. Adler (2003), Effective permeability of fractured porous media in steady state flow, *Water Resour. Res.*, 39(1), 1023.
- Gonzalez-Garcia, R., O. Huseby, J. Thovert, B. Ledésert, and P.M. Adler (2000), Three-dimensional characterization of a fractured granite and transport properties, *J. Geophys. Res.*, 105(B9), 21,387–21,401.
- Koudina, N., R. Gonzalez Garcia, J.-F. Thovert, and P. Adler (1998), Permeability of three-dimensional fracture networks, *Phys. Rev. E*, 57(4), 4466–4479.
- Lang, P.S.A. Paluszny, and R. W. Zimmerman (2014), Permeability tensor of three-dimensional fractured porous rock and a comparison to trace map predictions, *J. Geophys. Res. Solid Earth*, 119, 6288–6307.
- Nick, H.M., A. Paluszny, M. J. Blunt, and S. K. Matthai (2011), Role of geomechanically grown fractures on dispersive transport in heterogeneous geological formations, *Phys. Rev. E*, 84 (5), 056301.
- Olson, J. E. (2003), Sublinear scaling of fracture aperture versus length: An exception or the rule?, *J. Geophys. Res.*, 108 (B9), 2413.
- Paluszny A., and R. W. Zimmerman (2013), Numerical fracture growth modeling using smooth surface geometric deformation, *Eng. Fract. Mech.*, 108, 19–36.
- Pouya, A., and O. Fouche (2009), Permeability of 3D discontinuity networks: New tensors from boundary-conditioned homogenisation, *Adv. Water Resour.*, 32 (3), 303–314.
- Reeves, D. M., R. Parashar, G. Pohll, R. Carroll, T. Badger, and K. Willoughby (2013), The use of discrete fracture network simulations in the design of hor-

horizontal hills slope drainage networks in fractured rock, Eng. Geol., 163, 132-143.

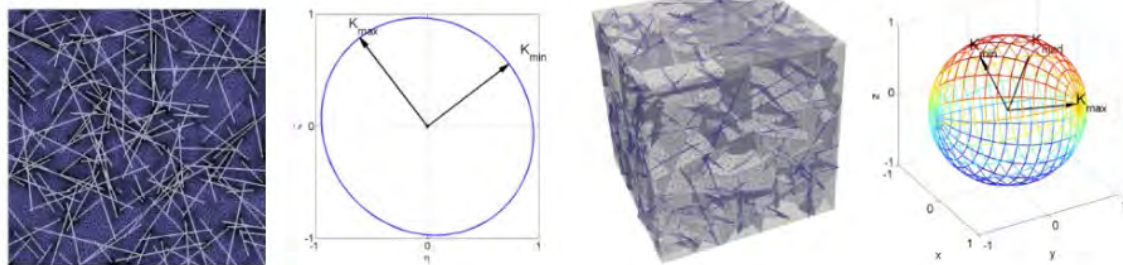
Rutqvist, J., C. Leung, A. Hoch, Y. Wang, and Z. Wang (2013), Linked multicontinuum and crack tensor approach for modeling of coupled geomechanics, fluid flow and transport in fractured rock, J. Rock Mech. Geotech. Eng., 5 (1), 18-31.

van Golf-Racht, T. (1982), Fundamentals of fractured reservoir engineering, 732 pp., Elsevier BV.

Wu, X., T. Hou, and Y. Efendiev (2002), Analysis of up-scaling absolute permeability, Discr. Contin. Dynam. Syst. Ser. B, 2 (2), 185-204. (not referred in

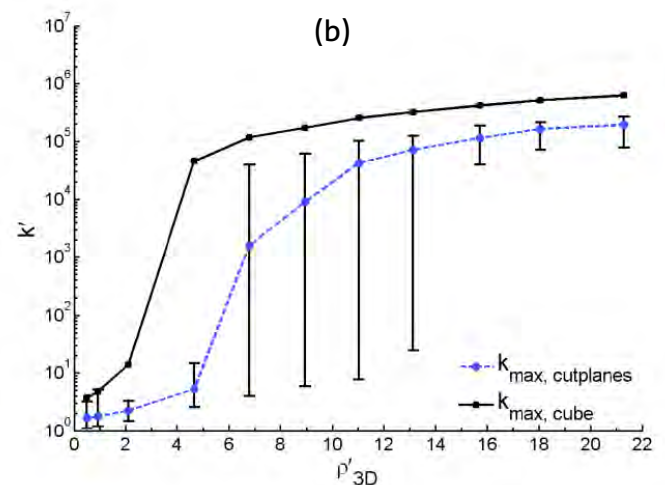
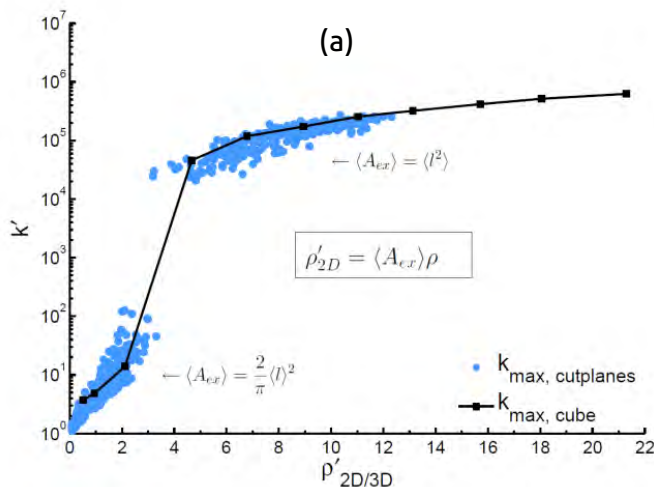


300 fracture cube DFM model, $\rho'_{3D} = 6.781$



900 fracture cube DFM model, $\rho'_{3D} = 21.256$

Medium and high fracture density fracture models and a random cut-plane of each. Ellipses and ellipsoids illustrate model equivalent permeability tensor.



Maximum principal permeability of cube models and cut-planes. (a) cut-plane density evaluated individually in terms of 2D density using the proposed alternative formulation of $\langle A_{ex} \rangle$. (b) 3D permeability is plotted in solid bold; the dotted line connects the mean values of the 2D permeabilities for that fracture density, with the range of values indicated by the extent of the vertical line.

Bridging the Gap from Well Scale to DFN Model.

Submitted by Doug Bearinger, Geology Advisor; Nexen Energy ULC

Introduction

Discrete Fracture Network (DFN) models can assist in the modeling of reservoir flow behavior. While simulation models with simplistic geometry may be manipulated to match short term reservoir performance, they may be misleading and of limited ability to predict long term production or the effect of development and completion design changes.

Well bores can intersect many natural fractures yet completely miss those that are significant to fluid flow at the reservoir scale. Seismic cannot resolve reservoir scale fractures but may yield attributes that respond to fracture intensity. The structural picture provided by seismic can provide the basis for prediction of fractures related to folding and faulting. This note will focus on methods to use fracture observations from wells to estimate the inputs needed for DFN modeling.

Defining mechanical layers

Layers of differing lithology and mechanical properties can contain different fracture sets. Fracture information should be gathered within a geomechanical unit framework. The geomechanical units can be de-

termined on the basis of natural fracture properties with the assistance of geomechanical property profiles and CDF distributions of fractures (Figure 1).

Fracture intensity measures and bias

Wells drilled perpendicular to a natural fracture set can provide good measures of fracture intensity and how it varies spatially. Generally, in most fields there are few wells drilled in this orientation for all fracture sets. It is essential that observational bias be reduced before attempting to upscale to a reservoir model. Vertical fractures are common in many plays and although vertical wells do not sample fracture frequency well, they can provide fracture height information, something that cannot be directly measured in other well orientations. Intensity measurements should reference a minimum size criterion. Core observations often provide an order of magnitude higher number of observed fractures compared to borehole image logs. In the case of intensely fractured shale reservoirs it is possible to measure enough fractures in core to determine size distributions. In this note the intensity measure will use the nomenclature of Dershowitz (1992). In this P system, the first subscript is the dimension of the sample area and the second subscript is the dimension of the fracture measurement.

Several methods to measure/de-bias fracture intensity data were reviewed. Terzaghi (1965) provided a correction for the intersection angle with a scanline. In practice this method works poorly for vertical wells and fractures as the correction approaches infinity if unconstrained. For a scanline of consistent orientation, the infinity problem can be avoided by computing the length of the vector perpendicular to the mean orientation of the fracture set.

$$P10_{\square} = \frac{\text{count}}{L \cos B}$$

Narr (1996) proposed an improved method that includes the diameter of the sample (core or borehole image). Berg (2012) recognized that fracture size also influenced the number of fracture intersections and proposed a calculation that included fracture size. He

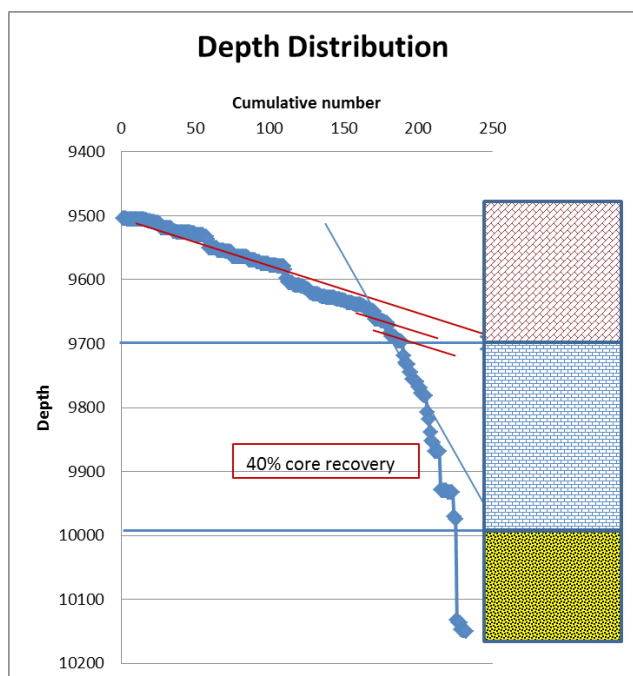
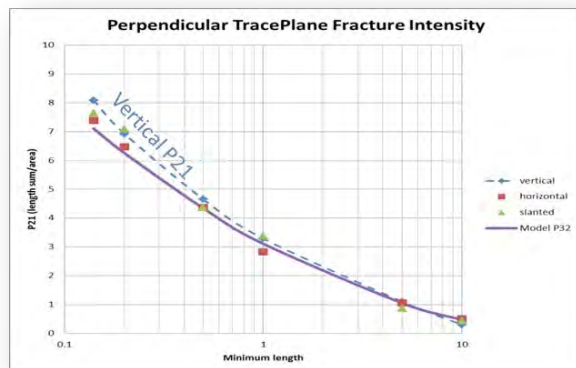
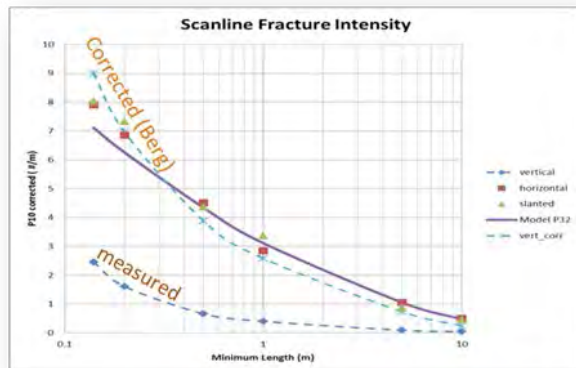


Figure 1.
Note the unique CDF slope for each lithologic unit.

also proposed that fracture intensity be measured as the sum of fracture trace lengths in a perpendicular projection to the fracture set (P21). This is then simply the sum of projected lengths over the area of projection. Both methods suggested by Berg were evaluated using a wellbore scale DFN model where the 3D fracture intensity is known. The perpendicular projection method performed best in all the tested well orientations and had a significant advantage in vertical wells (Figures 2a, 2b).



Figures 2a, 2b. DFN model testing of fracture intensity debias techniques.

Fracture size distribution

When there are sufficient fractures described it is possible to fit a size distribution function to the data. Care must be taken to avoid the tails of the data set that are affected by truncation and censoring. These artifacts give the data the appearance of a lognormal distribution. Power Law has been shown to fit many field fracture length observations and the extension-linkage process of fracture growth (Cladouhos & Marrett 1996). Some of the observed fractures will not terminate within the core. Given that the number of observations is often less than desired, it is recommended to fit a size distribution to all the measured

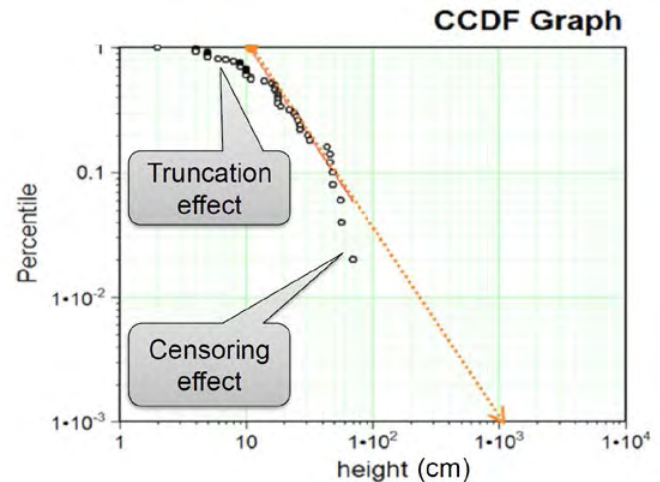


Figure 3. Fitting power law size distribution.

fracture lengths in addition to fracture lengths that are completely within the core (Figure 3).

Intensity-size scaling

To determine the P32 fracture intensity required for a reservoir scale model, intensities must be scaled taking the effects of size distribution into account. Thin bedded zones may have many bed bound fractures in core but fewer reservoir scale fractures that affect flow than thick bedded units that have fewer but longer fractures in core. The scale-up can either be done using a DFN model and progressively increasing the minimum fracture size or by sorting the core data by size and plotting the truncated fracture intensities. Note that the most intensely fractured zones in core observations may be the least intensely fractured at reservoir scale (Figure 4).

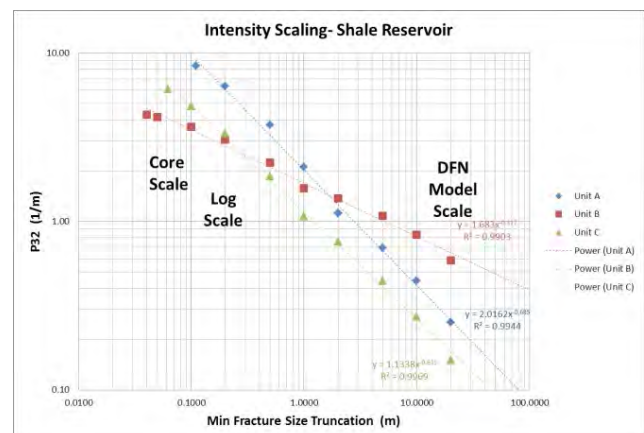
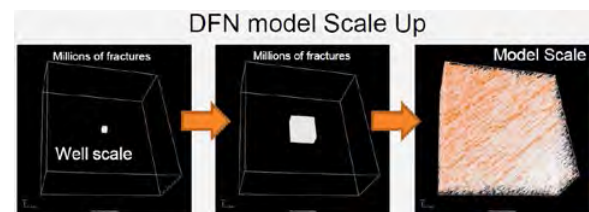


Figure 4. Fracture size-intensity scaling.

Assigning fracture properties

It is common practice to tie many fracture properties to fracture size. Larger fractures tend to have larger apertures and conductivity. Olson (2003) proposed that aperture tends to correlate with the square root of fracture size (Figure 5). Direct measurements in core and estimates from image logs can be used as constraints.

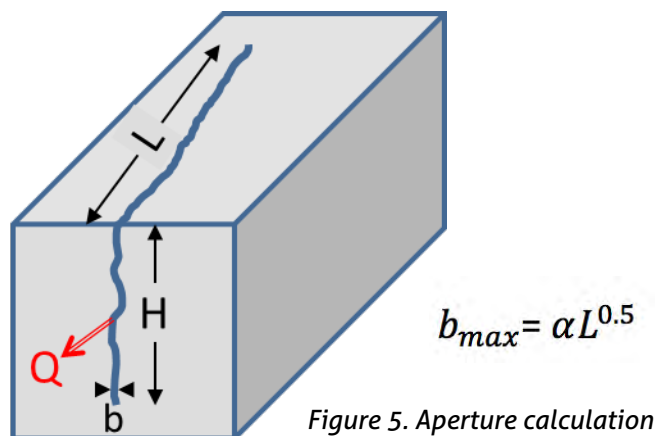


Figure 5. Aperture calculation

Core tests of conductivity without proppant (often called natural asperity samples in proppant embedment tests) are particularly useful. The conductivity versus normal stress relationship can be used to estimate aperture, permeability and conductivity (transmissivity) of fractures. The data can also be used to estimate normal fracture stiffness (Figure 6).

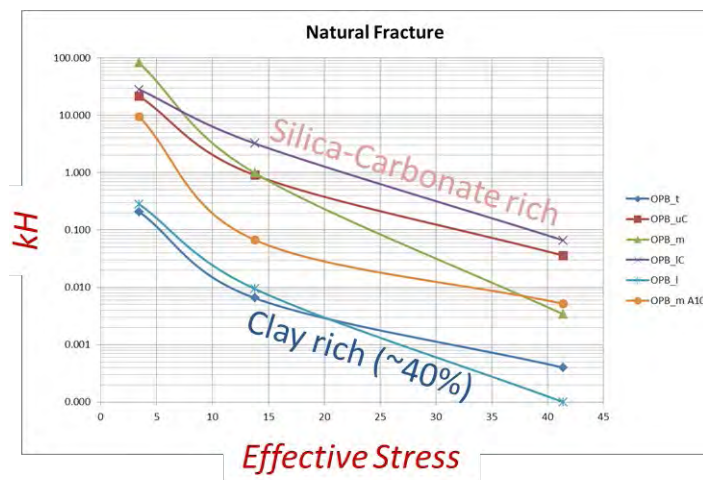


Figure 6. Fracture conductivity test results

Storage apertures used in a DFN model may need to be adjusted to account for the smaller fractures that have been truncated from the model. Although they may not significantly affect the fluid flow because of their lower transmissivity, they can significantly affect the movement of fluid by their storage capacity. For models that are used to simulate hydraulic stim-

ulation this is of great importance as most software uses volume balancing during the simulation. In a DFN simulation involving natural fractures this extra storage may be added to the fracture sets that intersect these omitted fractures. In other software, the fluid that invades the smaller fractures is considered as part of the fluid leak-off.

Fracture characteristics can also be estimated by simulating and matching well tests within a DFN model as shown in Figure 7.

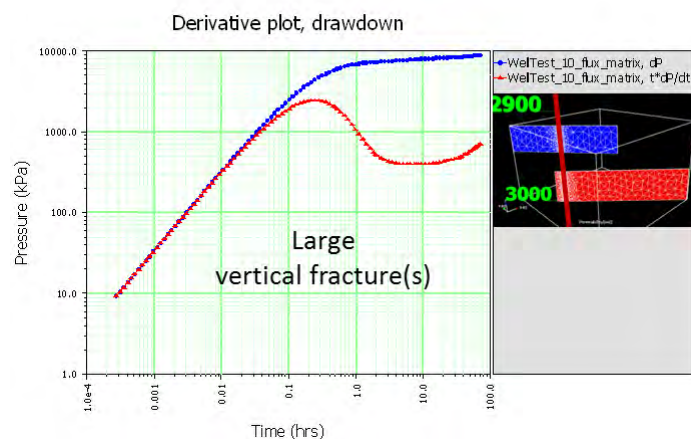


Figure 7. DFN well test simulation

In shale reservoirs, hydraulic pressure hits on offset wells can be used to find the fracture aperture, permeability and transmissivities that match the time of flight (Figure 8).

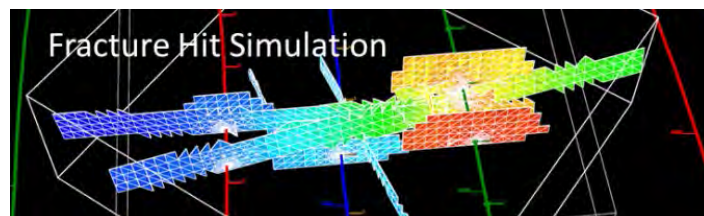


Figure 8. Fracture hit simulation

Validating the DFN model

Given the sparse nature of fracture data and the need for scale-up to a reservoir model it is advised to test the model against observations. For reservoirs that produce without stimulation, the DFN model can be tested against lost circulation events, gas kicks, imaged large aperture fractures and production log inflows. The size distribution and intensity-size scaling can be adjusted so that the modeled well/fracture intersections match the number of observed fracture indicators in wells.

Stimulated naturally fractured reservoirs are more challenging but methods are emerging to estimate producing fracture volume and producing fracture surface area (Zolfaghari et al, 2015, 2017, Adefidipe, 2014). Microseismic provides stimulated geometry and distribution in three dimensions. Injected fracture porosity can be estimated from the ratio of injected fluid volume to the stimulated reservoir volume. This is directly related to fracture porosity (a function of intensity and storage aperture).

The vertical distribution of stimulated fractures and microseisms is also dependent on fracture connectivity. At model scale, it is possible to lose connectivity if intensities fall too low. The natural fracture network can be analyzed for connectivity and fracture clusters to evaluate if the connectivity threshold has been exceeded. The connectivity of fractures at the boundaries of mechanical units can strongly influence the vertical growth behavior of hydraulic stimulations. In reservoirs with open conductive fractures it is possible for stimulation fluids to penetrate through "stress barriers" extending into other zones. Pressure and proppant hits on offset wells also place some constraints on the stimulated geometry.

Summary

Building a DFN model from well observations requires:

- Determining mechanical units
- Debiasing of fracture data
- Characterizing the fracture size distribution
- Scaling fracture intensity from well to model scale
- Assigning fracture properties that may also need to account for the fractures truncated from the model
- Validating that the upscaled model matches frequency of well intersections of reservoir scale fractures
- The model can be used to simulate the observed hydraulic stimulation geometries in unconventional reservoirs

Conclusion

Fracture data obtained from wellbores can be used to build realistic reservoir models when observational bias and scale differences are properly handled. DFN modeling tools provide the means to build fracture networks that match fracture observations and indicators. Whether building a DFN model for a conventional or unconventional reservoir, the DFN model should be tuned/validated with indicators of reservoir scale fractures such as drilling fluid losses or microseismic events. These models can either be used directly in DFN capable reservoir simulators or can be upscaled to equivalent porous media properties for grid based reservoir simulation.

References

- Adefidipe, A. A., Y. Xu, H. Dehghanpour and C. J. Virues, 2014. Estimating Effective Fracture Volume From Early-Time Production Data: A Material Balance Approach. SPE/CSUR Unconventional Resources Conference – Canada, 30 September–2 October, Calgary, Alberta, Canada. Paper SPE-171673-MS. <http://dx.doi.org/10.2118/171673-MS>
- Baecher, G. B. and N. A. Lanney, 1978. Trace Length Biases In Joint Surveys. In Proceedings, 19th U.S. Symposium on Rock Mechanics (USRMS), 1-3 May, Reno, Nevada, pp. 56-65.
- Berg, C.R., 2012, The Effect of Fracture and Borehole Orientation on Fracture Frequency and Density: in <http://www.resdip.com/docs/fracture%20orientation.pdf>.
- Dershowitz, W. S. and H. H. Herda, 1992. Interpretation of fracture spacing and intensity. In Proceedings, The 33th U.S. Symposium on Rock Mechanics (USRMS), 3-5 June, Santa Fe, New Mexico. pp. 757-766.
- Xu, Y., Y. Fu, D. O. Ezulike, H. Dehghanpour and C. J. Virues, 2015. Modeling Two-Phase Flowback Data Using an Open Tank Model. SPE/CSUR Unconventional Resources Conference, 20-22 October, Calgary, Alberta, Canada. Paper SPE-175923-MS. <http://dx.doi.org/10.2118/175923-MS>
- Zolfaghari, A., H. Dehghanpour, E. Ghanbari and D. Bearinger, 2016. Hydraulic Fracturing, Shale Gas Development, Flowback Data Analysis, Material Balance Analysis, Fracture Effectiveness. SPE Journal, Vol. 21, SPE-168598-PA, pp. 233-244. <http://dx.doi.org/10.2118/168598-PA>

■ SedHeat Workshop

ARMA is pleased to join Itasca Consulting Group, Texas Christian University Energy Institute, and the University of Utah in sponsoring the fourth Sed-Heat Workshop: Unlocking the Energy Elephant to be held 1-4 March 2017 at the Marriott University Park Hotel, Salt Lake City, Utah, USA. The workshop is supported by a grant from the National Science Foundation.

The SedHeat workshop community focuses on efforts to advance sedimentary-geothermal energy toward significant breakthroughs and development to its full potential. The workshop explores the basic science and engineering of geothermal energy in high-temperature sedimentary basins. Experts in geothermal and related subsurface fields will identify challenges and issues associated with economically viable production of heat from sedimentary basins. General topics for discussion include:

Geology of sedimentary basins;

Reservoir characterization and engineering;

Drilling and completion;

Co-production with oil and gas;

Induced seismicity and environmental impacts; and

Regulatory frameworks and economic assessments.

The workshop is open to ARMA members (subject to limited seating). Registration and further information can be found at www.itascacg.com/news/sed-heat-unlocking-the-energy-elephant.

■ DFNE 2018 Conference

ARMA is sponsoring the Second International Discrete Fracture Network Engineering Conference to be held on 20-22 June 2018 in Seattle, Washington, USA. The conference will be held in conjunction with ARMA's **52nd U.S. Rock Mechanics / Geomechanics Symposium** scheduled for 17-20 June 2018 at the Westin Seattle Hotel. The conference will examine DFN theory and fundamentals; oil, gas and geothermal energy; DFN approaches for underground and surface mining; and DFN approaches for infrastructure/geohazards.

For further information see: www.dfne2018.com.

■ New York City 2019

New York City has been selected as the site of the 2019 53rd U.S. Rock Mechanics / Geomechanics Symposium on 23-26 June 2019. The symposium will be held at the New York Marriott at the Brooklyn Bridge. Evangelia Ieronymaki from Manhattan College and Bruno Goncalves da Silva from the New Jersey Institute of Technology are to co-chair the event.

Stay tuned for further details.

