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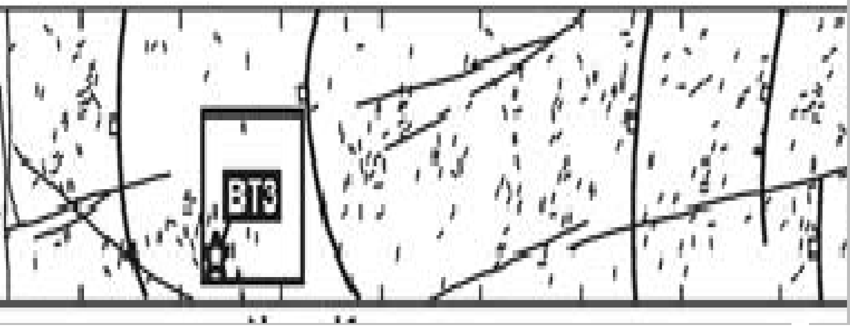

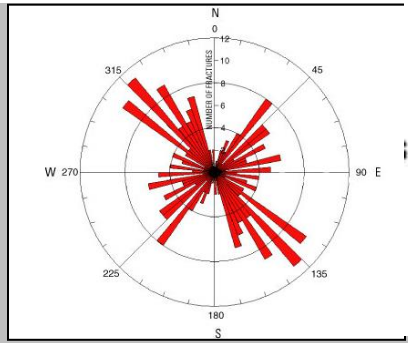

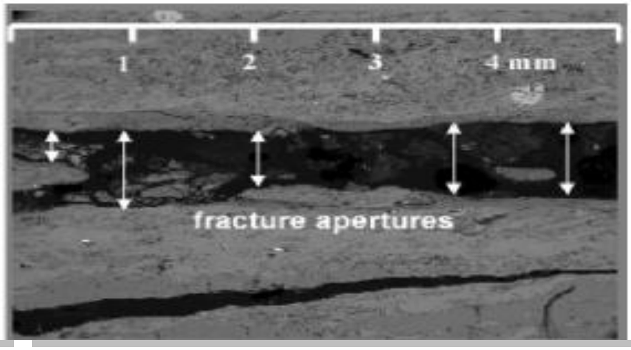

CONCEPTUAL REPRESENTATIONS OF FRACTURE NETWORKS AND THEIR EFFECTS ON PREDICTING GROUNDWATER TRANSPORT IN CRYSTALLINE ROCK

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Introduction

- Problem Statement
  - The fracture network are very complex system.
  - Their properties are usually inferred from the observations at rock outcrops, exploratory boreholes, quarries, and tunnels.
  - These data are inherently spatially limited and a stochastic model is required to extrapolate the fracture properties over the large volumes of rocks.
- This study
  - Describes three different methods of generating fracture networks developed for use in the fractured continuum model (FCM)
  - Provides a few examples of how these methods impact the predictions of simulated groundwater transport.
- Transport simulations using FCM will be presented next: “Numerical Modeling of Flow and Transport in Fractured Crystalline Rock” (Hadgu, Kalinina, Klise and Wang).

Continuum Fractured Model (FCM)

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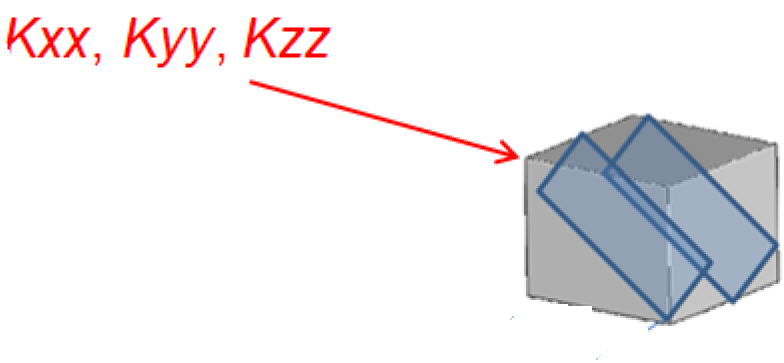


<u>Grid Block Porosity</u>

$$e_i = \frac{\sum V_f}{V_{gr}}$$

$$e_f = A_f \cdot b$$

$\sum V_f$ - total volume of fractures
Vgr - grid block volume
Af - fracture area

<u>Grid Block Permeability (Chen, 1999)</u>

$$k_{ij} = \frac{b^3}{12d}\begin{bmatrix} (n_2)^2 + (n_3)^2 & -n_1 n_2 & -n_3 n_1 \\ -n_1 n_2 & (n_3)^2 + (n_1)^2 & -n_2 n_3 \\ -n_3 n_1 & -n_2 n_3 & (n_1)^2 + (n_2)^2 \end{bmatrix}$$

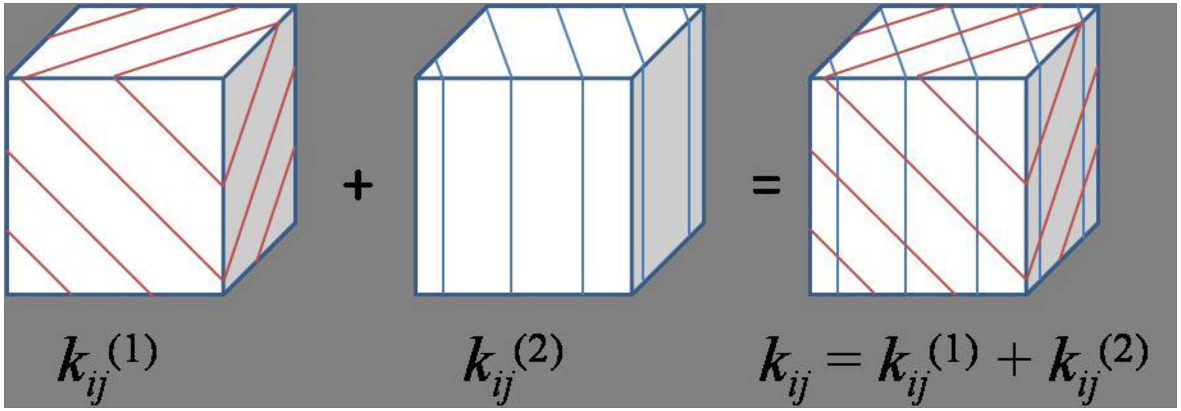
$$n_1 = Cos\left(\alpha \frac{\pi}{180}\right) xSin(\omega \frac{\pi}{180})$$

$$n_2 = Cos\left(\alpha \frac{\pi}{180}\right) xCos(\omega \frac{\pi}{180})$$

$$n_3 = -Sin(\alpha \frac{\pi}{180})$$

b - fracture aperture
d - fracture spacing
α - fracture plunge (90^0 - dip)
ω - fracture trend (strike - 90^0)

FCM Extension to Multiple Fracture Sets



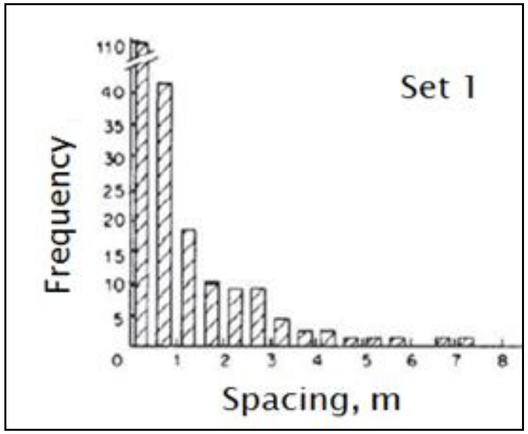
$$k_{ij}^{*} = \sum_{m=1}^{N} k_{ij}^{m}$$

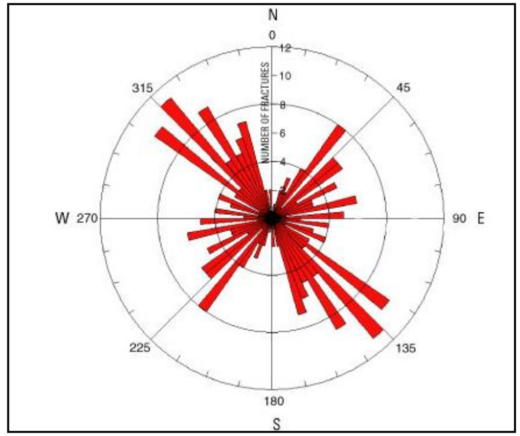
k_{ij}^{m} is permeability tensor of fracture set m
N – number of fracture sets

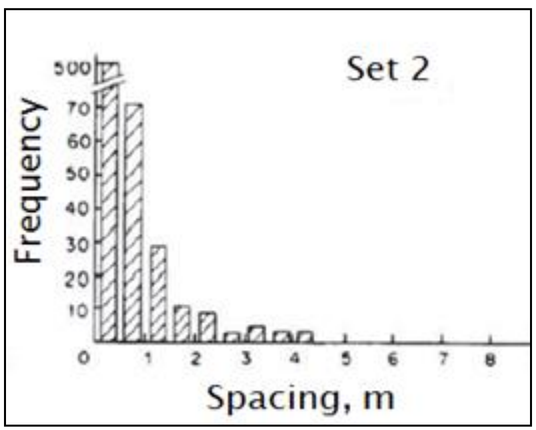
- Transport in grid blocks with fracture is in the fraction of the grid block representing total fracture volume.
- Transport in the grid block without fractures is in the pore volume defined by the matrix porosity.

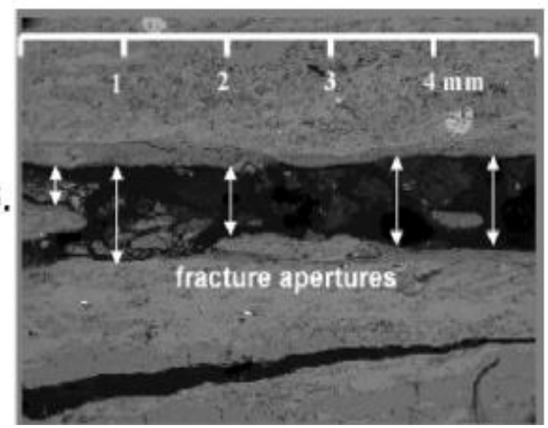
Fracture Properties: Measured and Inferred

Measured

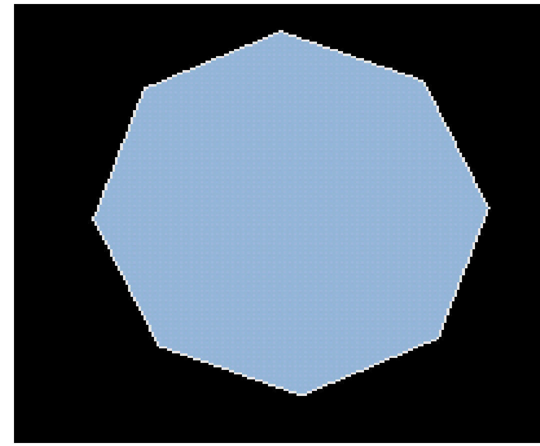


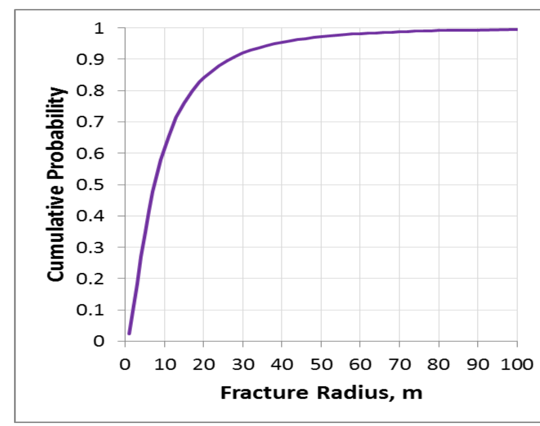




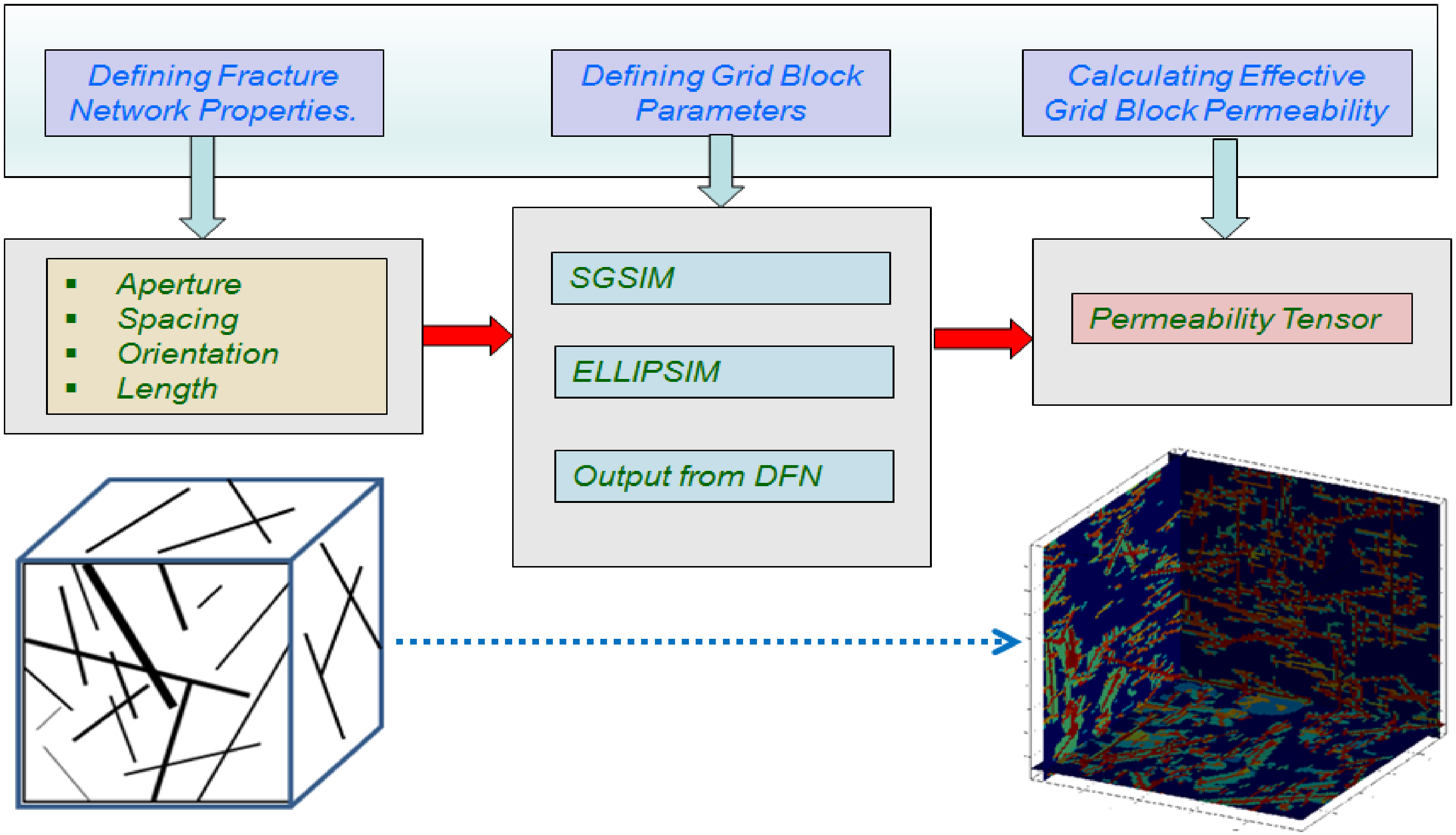


Inferred





FCM Methods for Generating Permeability Field from Fracture Network Parameters



Test Case Fracture Properties

Fracture Set	Mean trend (degrees)	Mean plunge (degrees)	κ	α	R_u (m)	R_0 (m)	Number of fractures
North-South Vertical	90	0	22	2.5	500	15	2,100
East-West Vertical	0	0	22	2.7	500	15	2,000
West-East Horizontal	360	90	10	2.4	500	15	2,300

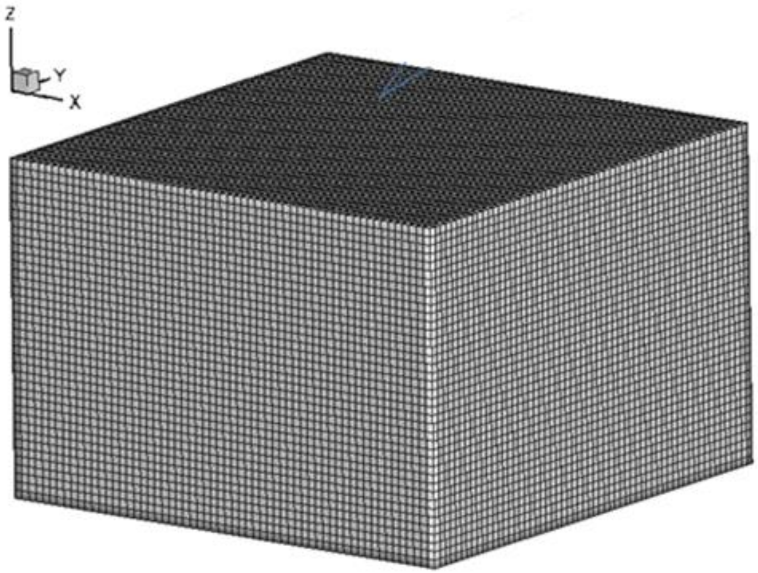
Fracture properties are loosely based on the SKB site in Sweden.

Fracture Aperture: function of fracture radius.

Domain:
- 1000 m x 1000 m x 1000 m

Grid block size:
- 10 m x 10 m x 10 m

Number of grid blocks:
- 1,000,000



Fracture Network Generation with SGSIM

SGSIM:
- Correlation Ranges in x, y, z
- Correlation angles in x, y, z

→

Spatially Correlated Number Px,y,z

→

Spacingx,y,z(Px,y,z)
Strikex,y,z(Px,y,z)
Dipx,y,z(Px,y,z)

↑
Any distribution can be defined.

- Number of fractures k in a grid block is calculated using Poison distribution $f(k,\lambda)$.
- Probability $f(k,\lambda)$ is assigned to each grid block using P_{xyz}
- Correlation Ranges in x, y, z – based on fracture radius
- Correlation angles in x, y, z – based on fracture orientation
- Fracture aperture (b) can be defined by a distribution or calculated as a function of fracture radius.

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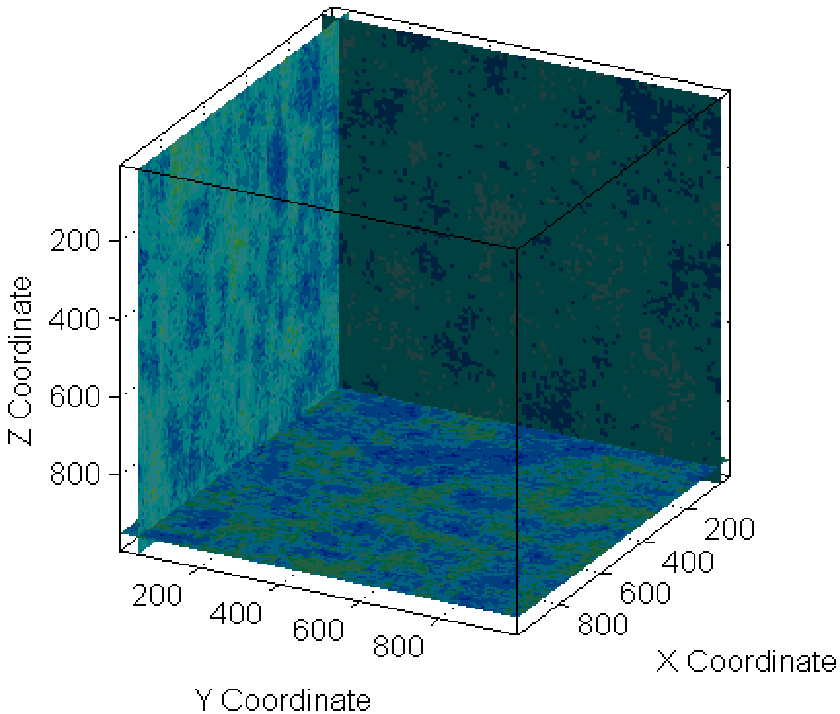
Example of SGSIM Permeability Field

- No assumption regarding fracture shape is required.
- Aperture, spacing, and orientation are defined by pdfs based on field observations.
- An exact number of fractures cannot be generated.

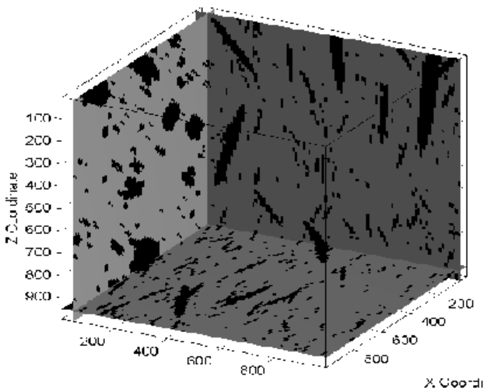


Fracture Network Generation with ELLIPSIM

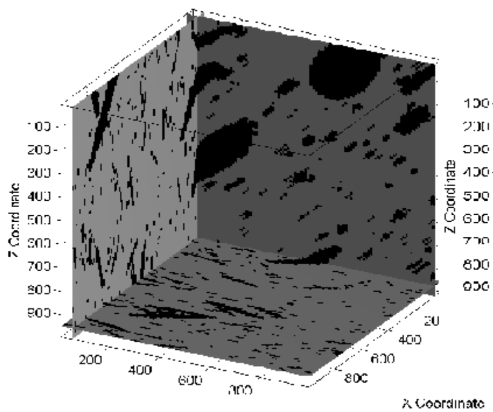
- Ellipsim is a Boolean simulation program.
- Ellipsim generates a specified number of ellipses.
- Each ellipse set represents a specific fracture set.
- Ellipse centers are randomly placed within the modeling domain.
- The ellipse radius and orientation are drawn from specified probability distributions.
- The grid blocks located within a specific ellipse are assigned the radius and orientation of this ellipse.
- The grid blocks that do not belong to any ellipse are considered to be matrix blocks.
- The fracture aperture is calculated from fracture radius.

Example of Three Fracture Sets Generated with ELLIPSIM

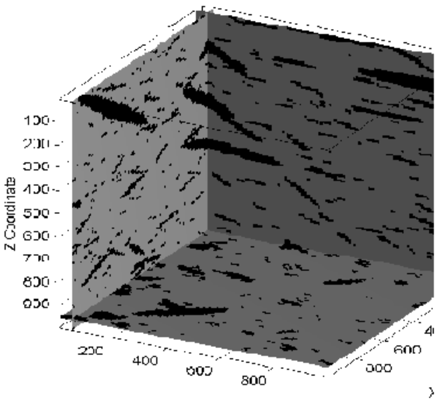
Vertical Fractures N-S



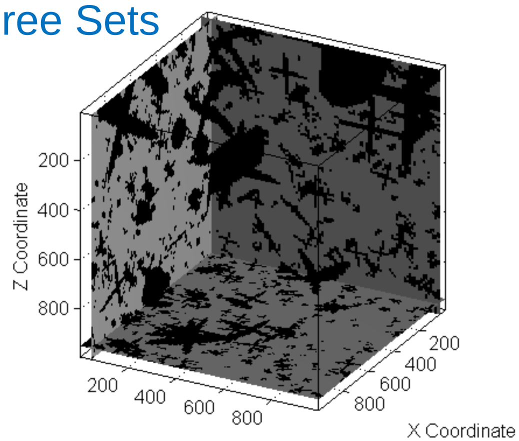
Vertical Fractures E-W



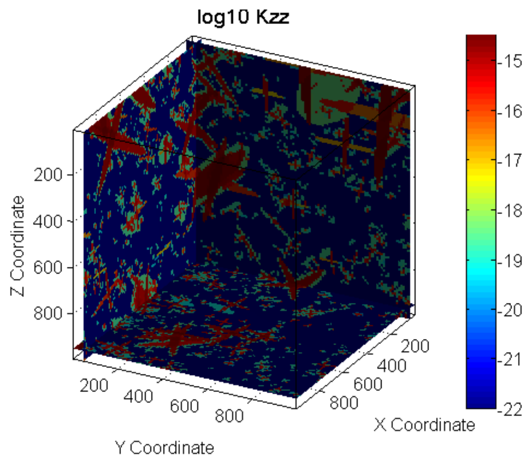
Horizontal Fractures W-E

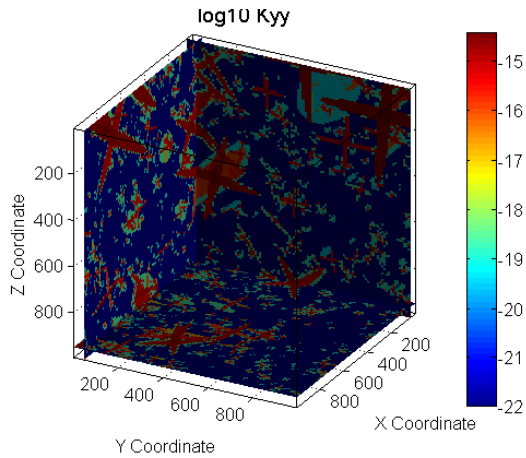


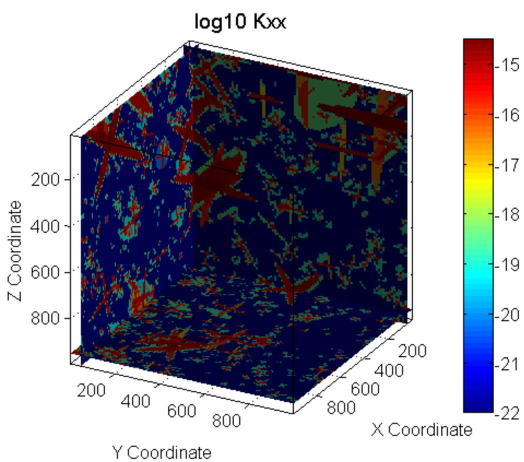
All Three Sets



kxx, kyy, and kzz Permeability Fields for the Fracture Network with Three Fracture Sets

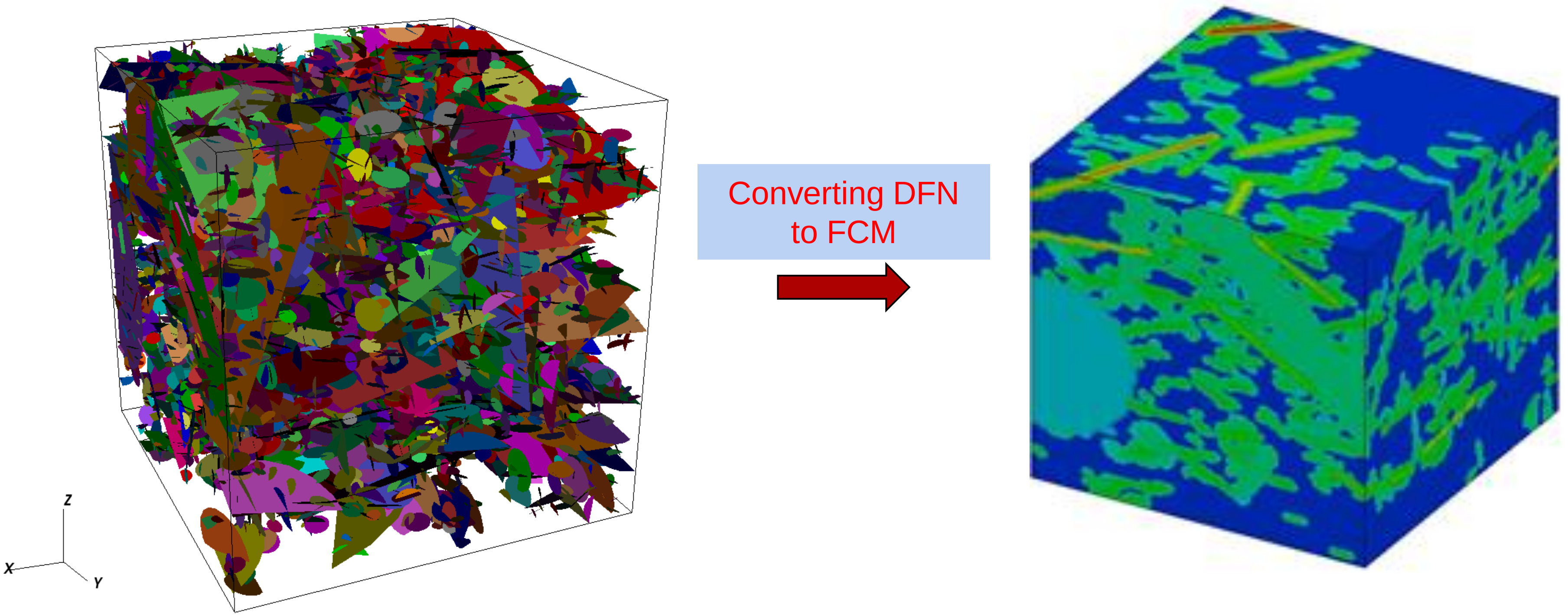






Fracture Network Generation by Converting DFN Output

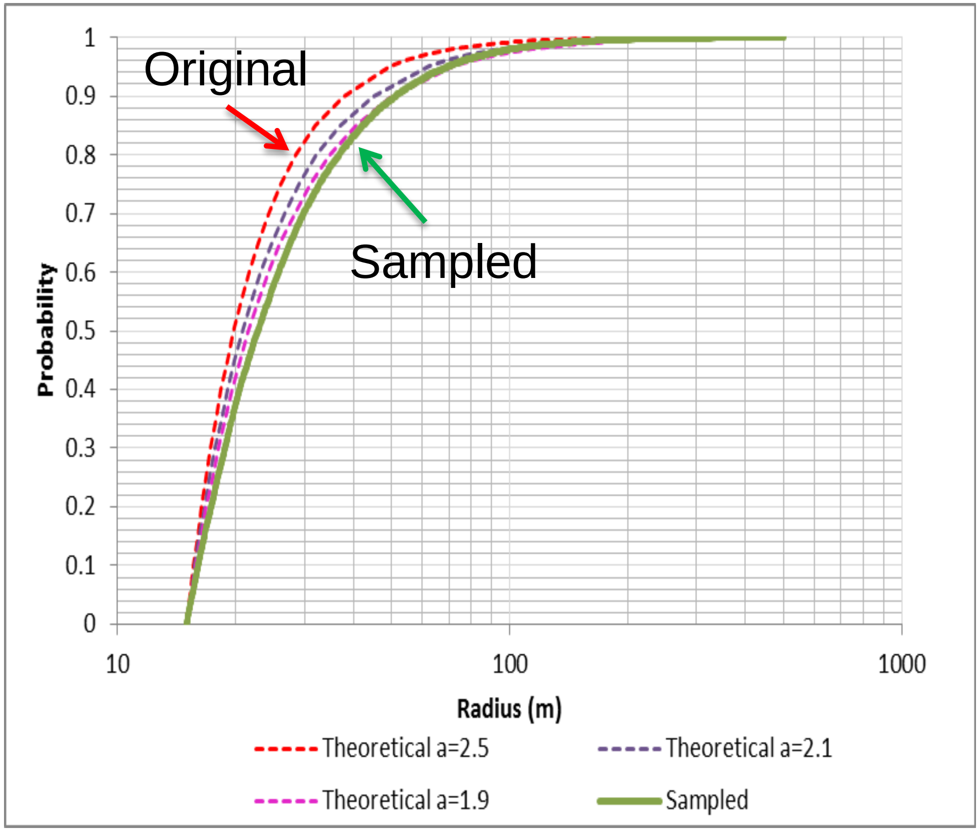
Example of One Realization of Fracture Network



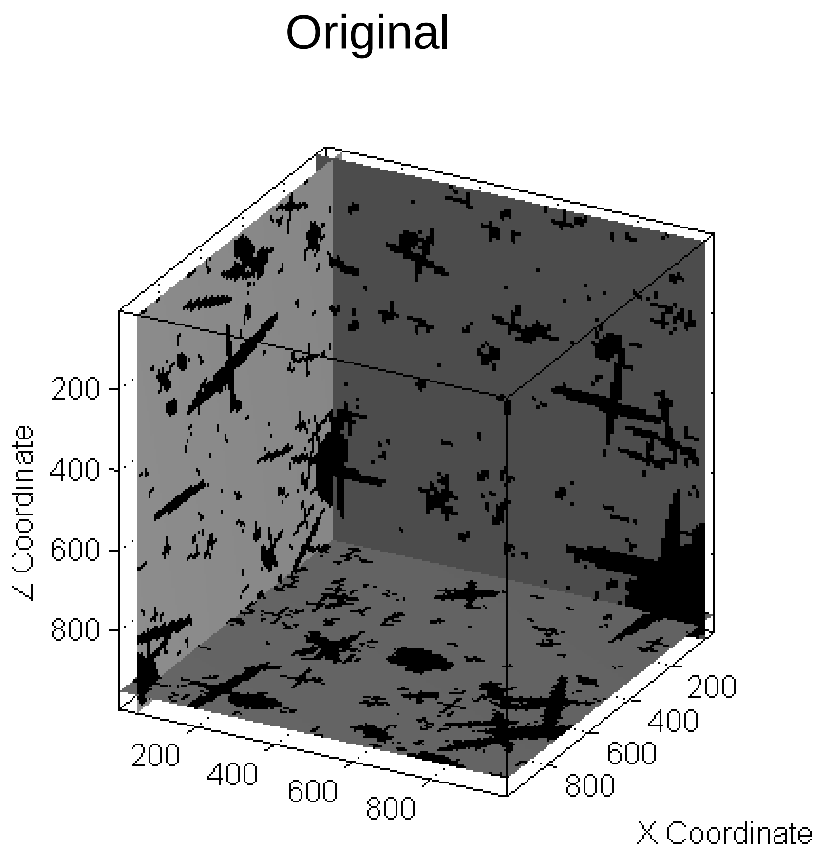
Fracture networks generated with DFN are connected because it is required for the flow and transport simulations.

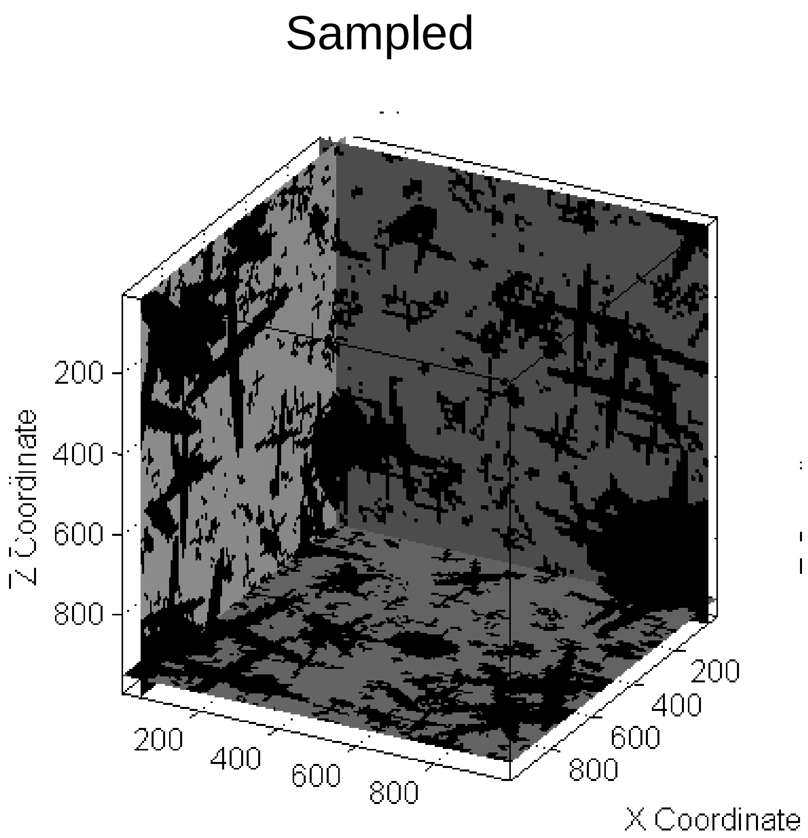
Fracture Network Connectivity

- DFN fracture network is generated iteratively to remove not connected clusters and to generate new fractures to assure fracture connectivity.
- This process may result in altering fracture radius distributions.

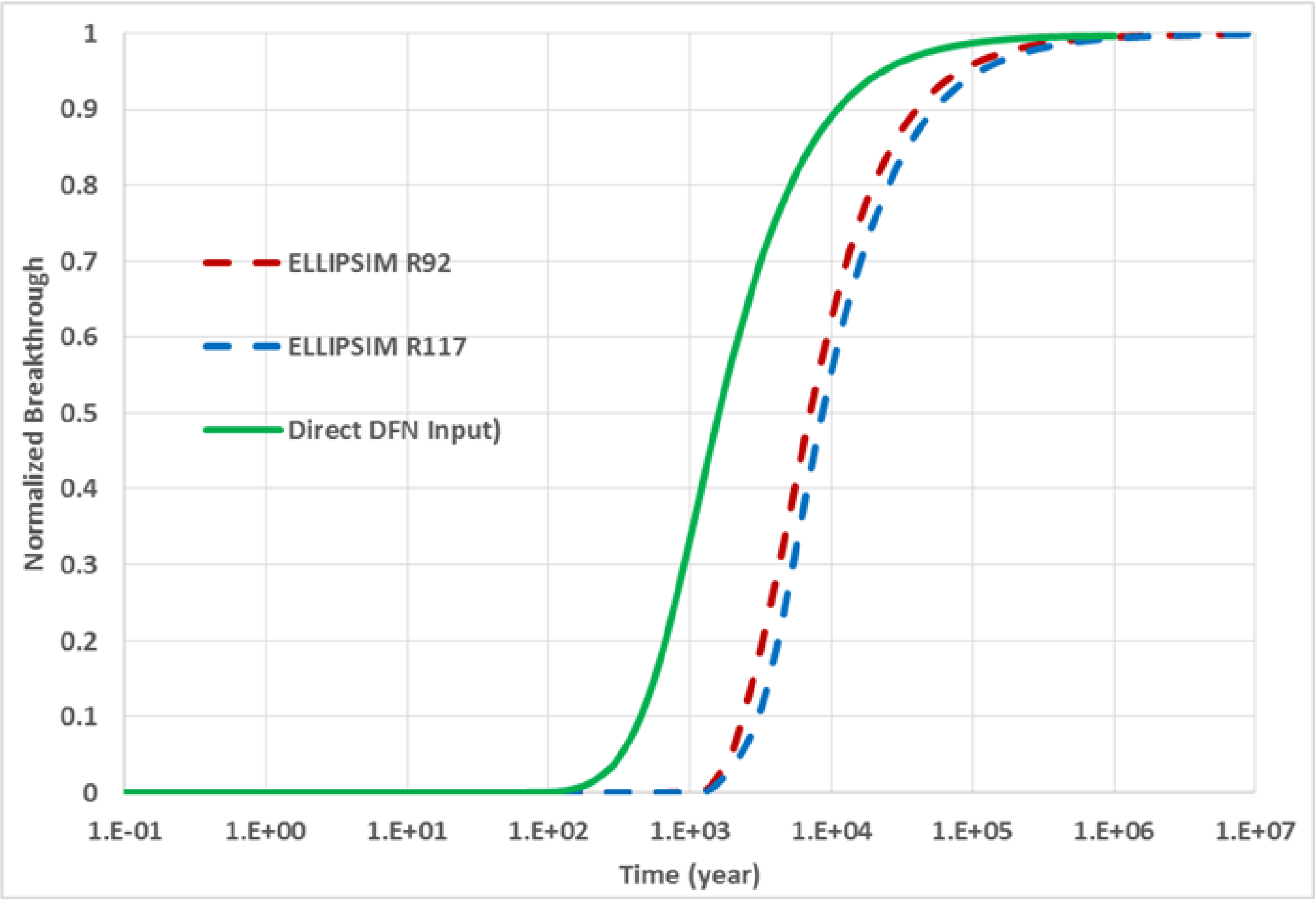


Fracture Network with Original and Sampled Fracture Radius Distributions

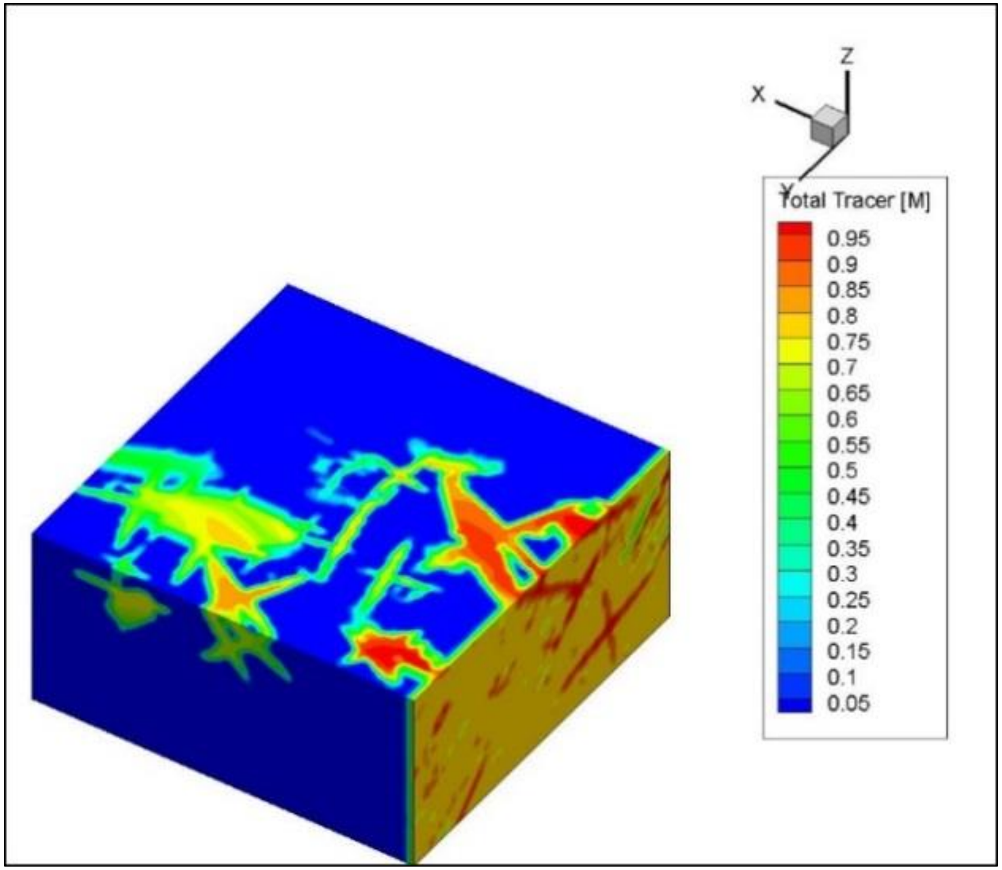




Breakthrough Curves for ELLIPSIM and DFN Based Fracture Networks



Tracer Transport Results at 1,000 Years for ELLIPSIM Fracture Network



- 6 realizations out of 50 resulted in the continuous flow and transport.
- The probability of the fracture network to be connected is ~ 12%.

Conclusions

- While the same fracture data are used as an input, the resulting fracture networks reflect the differences in the underlying assumptions and are affected by the method-specific limitation. .
- This is especially important to understand in the situations when little data are available and the conditioning of the fracture network properties using the actual observations is not possible.
- The differences in the fracture networks can result in significant differences in the predictions of the flow and transport.
- The connectivity of the fracture network has great importance. However, caution should be use in generating connectivity.
- The sparse fracture networks may not be connected.
- The selection of an appropriate method should be based on the site-specific considerations.
- The selection should be based on the comparison between the different methods. This especially concerns the capability of the method to reproduce the results of field tests.