Used Fuel Disposition Campaign

DFN-FCM FLOW AND TRANSPORT SIMULATIONS IN CRYSTALLINE ROCK

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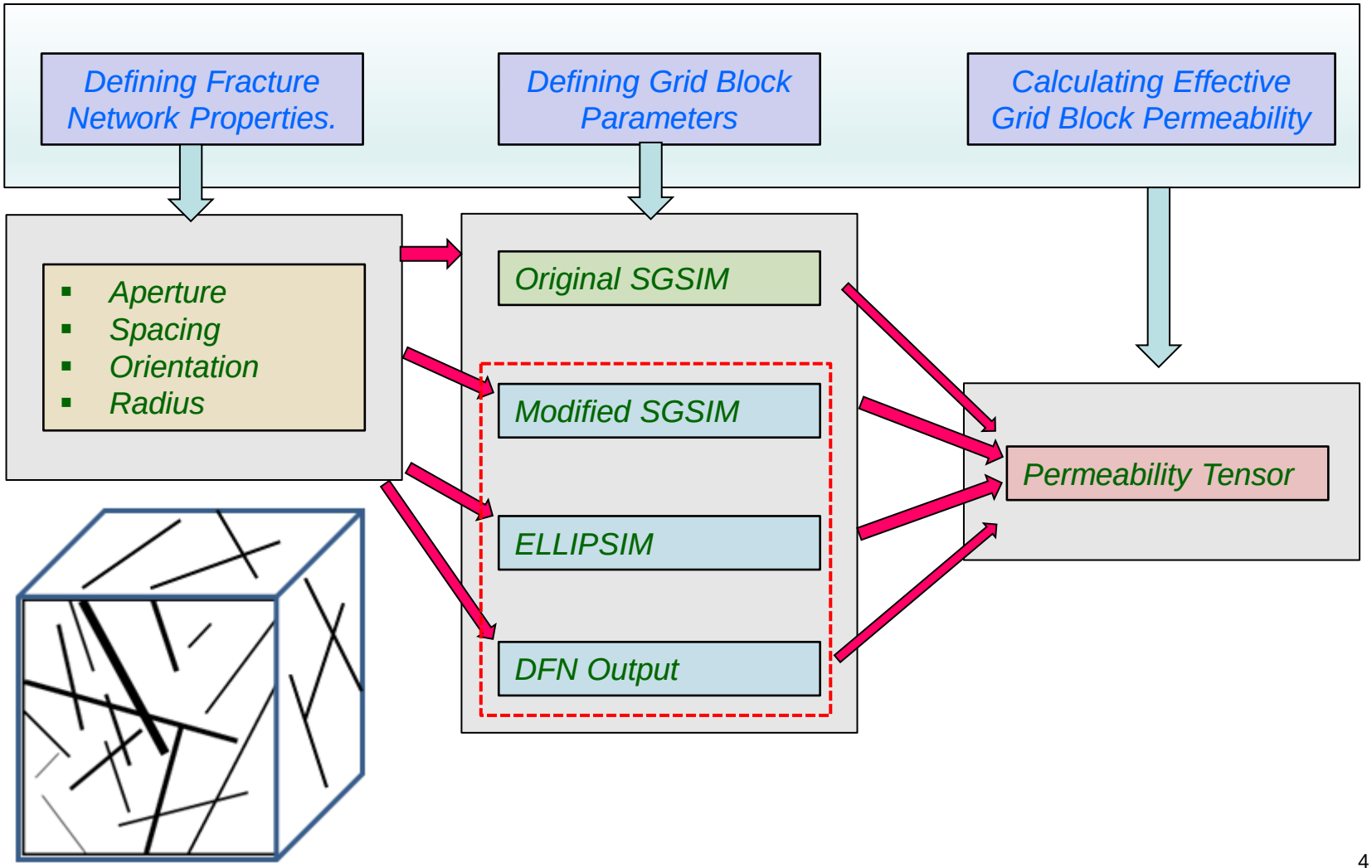
Fracture Continuum Model (FCM)

- **The Fractured Continuum Model (FCM) incorporates fully three-dimensional representations of multiple independent fracture sets.**
- **Based on discrete fracture and effective continuum approaches (McKenna and Reeves, 2005, Kalinina et al. 2012, and Hadgu et al. 2016).**
- **FCM applications:**
  - Multiple sets of natural and induced fractures with different orientations.
  - Different fracture spacing and aperture in different fracture sets.
  - Different fracture density with depth

FCM Approach

- **Uses method developed by Chen et al. (1999) to compute permeability tensors as a function of fracture parameters**
- **Fracture parameters are: strike, dip, aperture and spacing of each fracture set (defined as probability distributions)**
- **Fracture parameters are defined for each block of uniform orthogonal mesh using 3 different methods:**
  - Sequential Gaussian Simulation SGSIM (FY15)
  - Ellipsim (FY16)
  - DFN generated output (FY16)

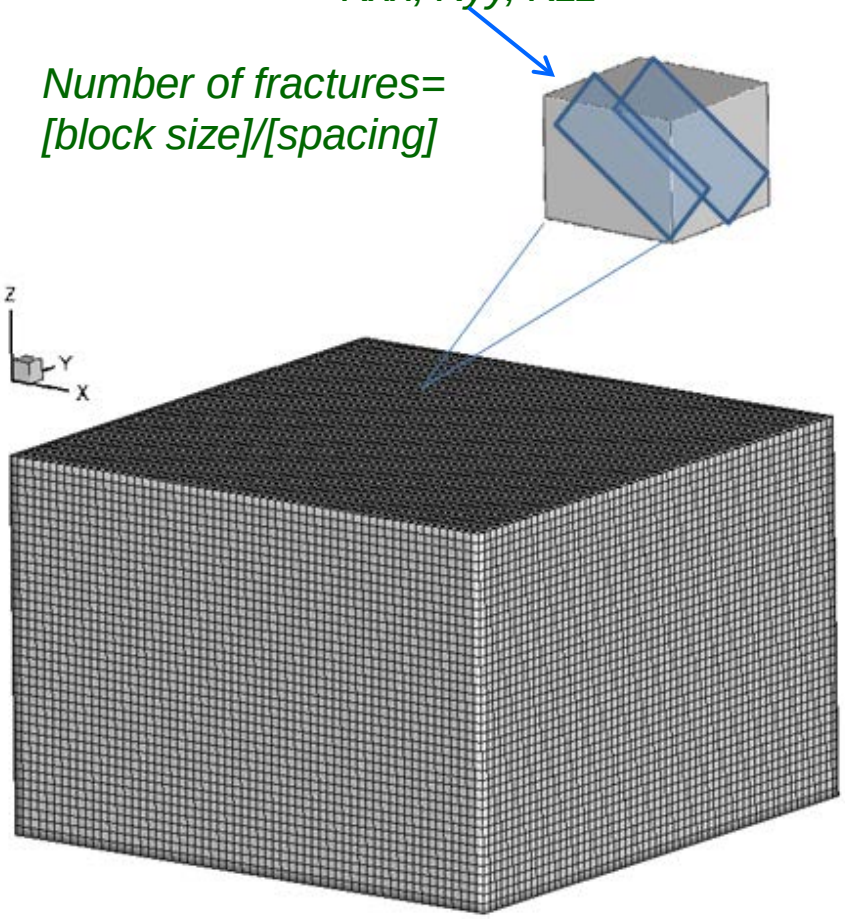
Evolution of FCM Approach



Definition of Grid Block Permeability Tensor (same for all methods)

Kxx, Kyy, Kzz

Number of fractures= [block size]/[spacing]



Permeability of grid block with one fracture set

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

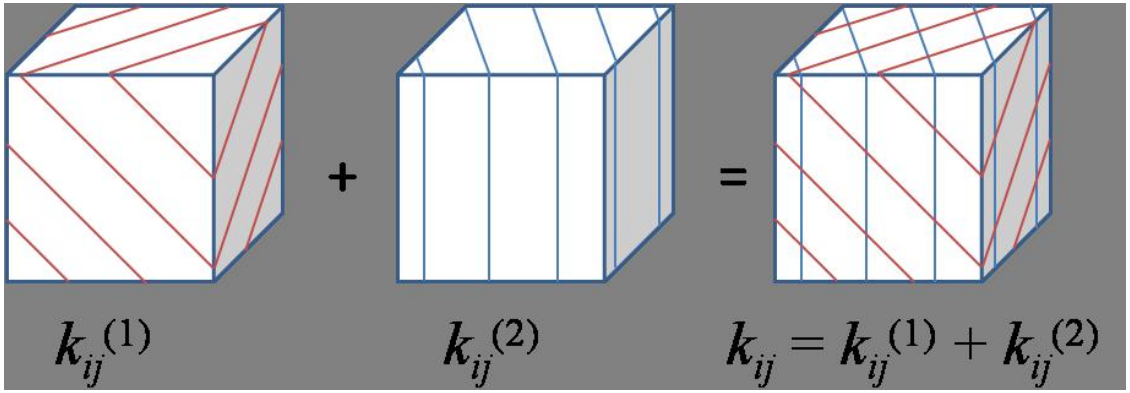
$$n_1 = Cos\left(\alpha \frac{\pi}{180}\right) xSin(\omega \frac{\pi}{180})$$

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

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

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

Permeability of Grid Block with Multiple Fracture Sets



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

k_{ij}^{m} is permeability tensor of fracture set m

<u>Assumption:</u> The summation assumes that the total porosity within a grid-cell changes very little.

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Definition of Fracture Parameters in a Grid Block: I. Sequential Gaussian Simulation (SGSIM)

Original SGSIM Method

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

→ *Spatially Correlated Number Px,y,z*

→ *Fracture Parameters:*
Spacing$_{x,y,z}$(Px,y,z)
Aperture$_{x,y,z}$(Px,y,z)
Strike$_{x,y,z}$(Px,y,z)
Dip$_{x,y,z}$(Px,y,z)

↑ *Any distribution can be defined.*

FY15 Modifications

Number of fractures k in a grid block is calculated using Poison distribution f(k,λ).

Probability f(k,λ) is assigned to each grid block using spatially correlated number 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) is calculated as: $b = \gamma \cdot R^{\omega}$

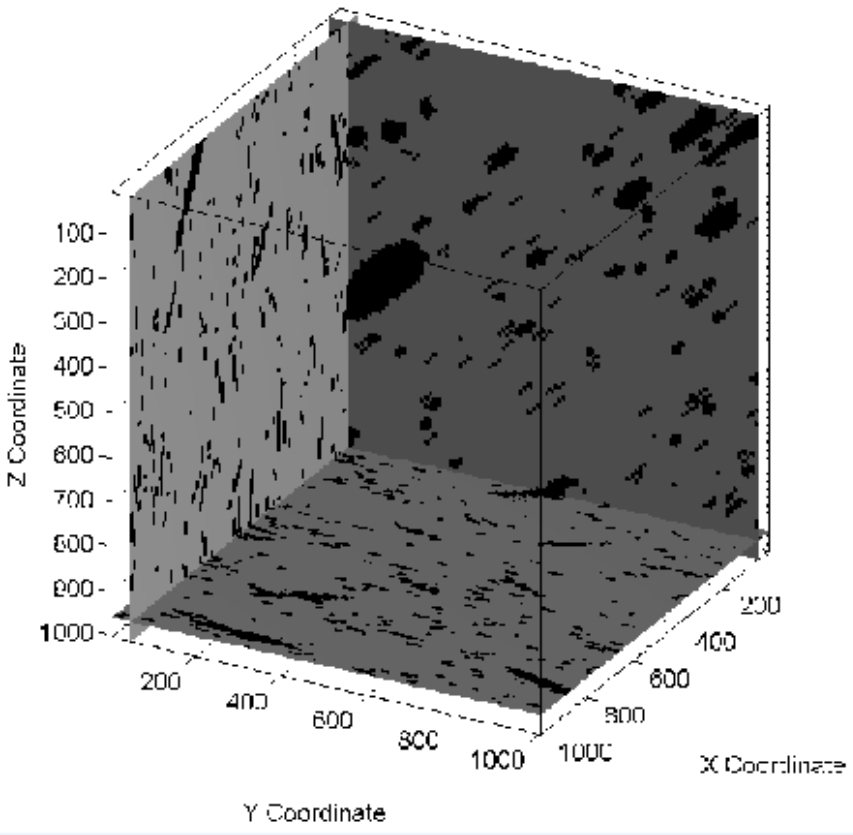
where R is fracture radius distribution and γ and ω are parameters.

Fracture Plunge (α) and Trend (Θ) are defined with univariate Fisher distribution.

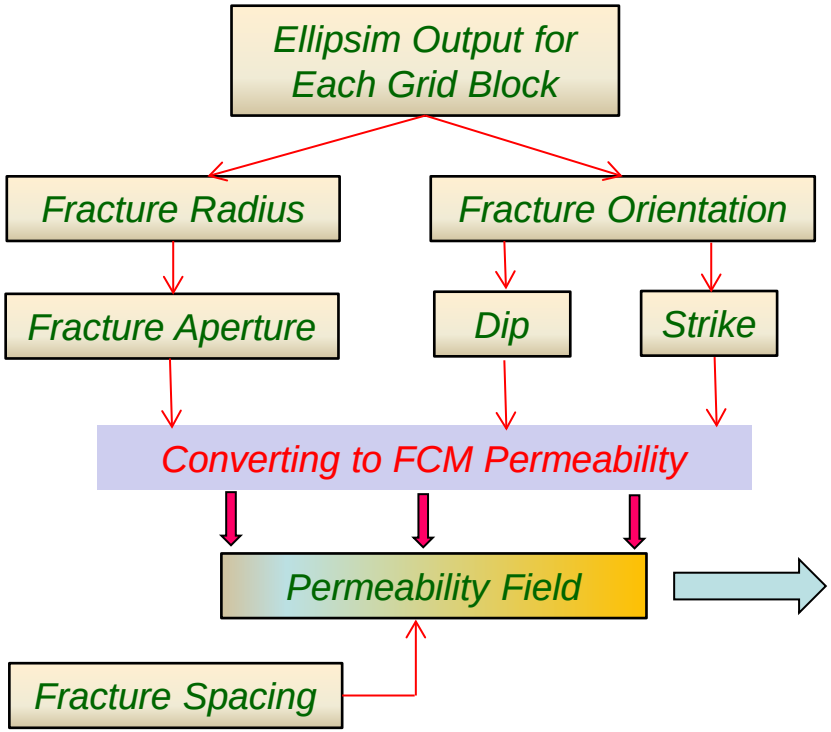
Definition of Fracture Parameters in a Grid Block: II. Boolean Simulation of Ellipsoids (Ellipsim)

- *Ellipsim generates a specified number of ellipses (FY16 modification).*
- *Each ellipse set represents a specific fracture set.*
- *Ellipse centers are randomly placed within the modeling domain.*
- *The ellipse radius is drawn from the power-law distribution.*
- *The ellipse orientation is drawn from the triangular distribution approximating Fisher distribution (FY16 modification).*
- *The grid blocks located within a specific ellipse are assigned its radius and orientation (FY16 modification).*

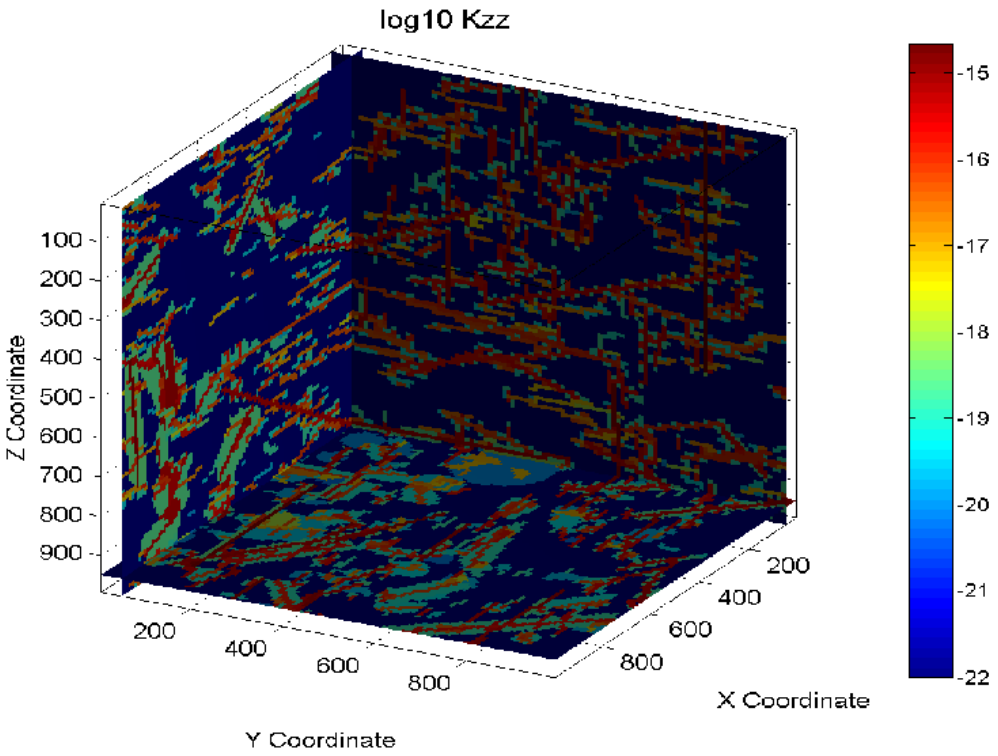
Example of One Fracture Set with 2,300 E-W Trending Fractures



Converting Ellipsim Output to FCM Permeability (continued)



Example of Permeability Field with 3 Fracture Sets (6,500 fractures)



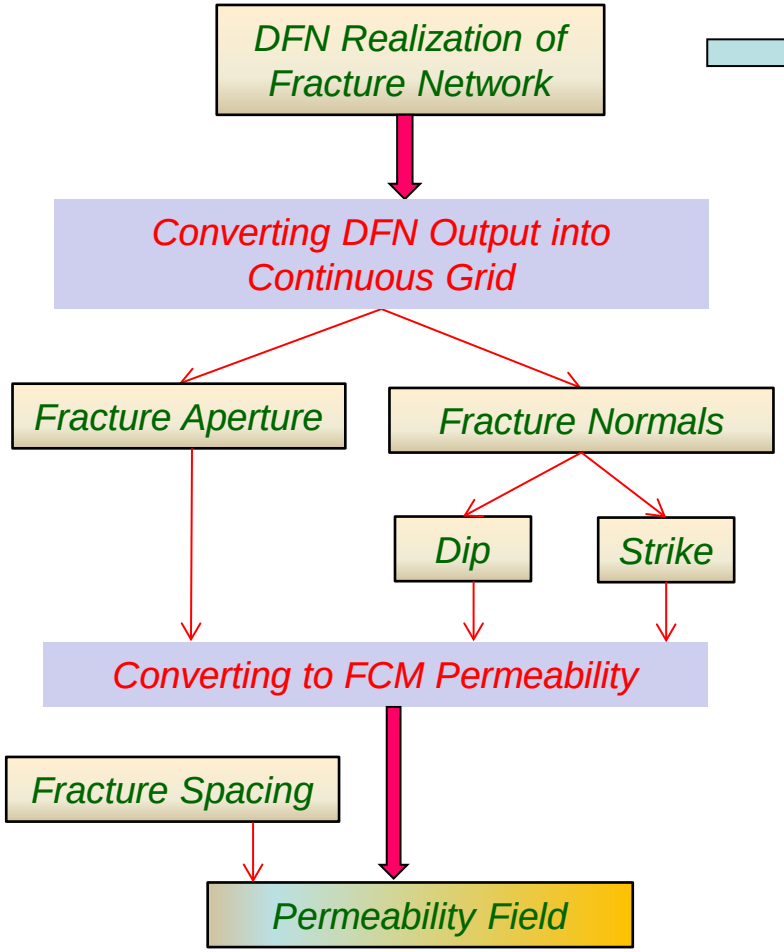
Aperture (b) is calculated from radius R as:

$$\log(\sigma) = \log(\gamma \cdot R^{\omega}), \qquad \sigma = \frac{b^3}{12}\frac{\rho g}{\mu}$$

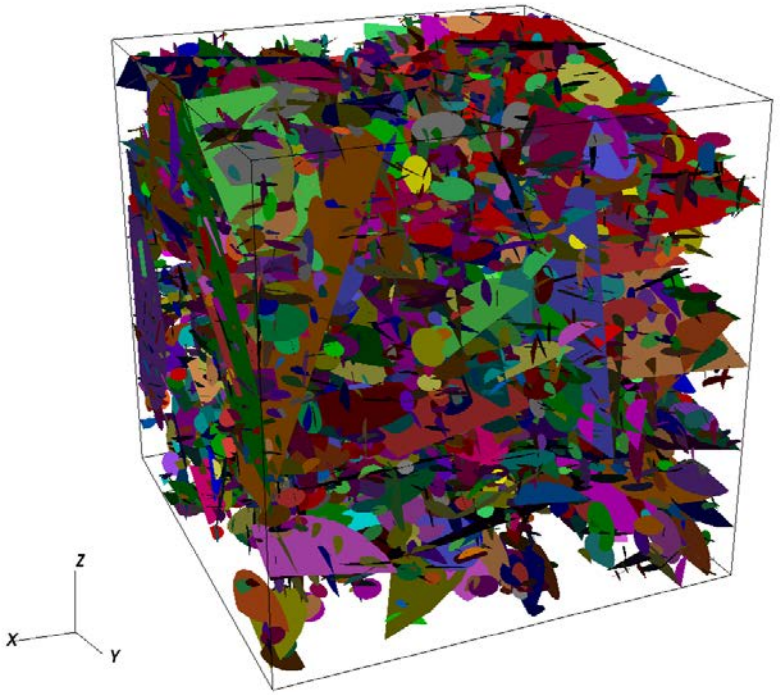
σ is fracture transmissivity, γ and ω are parameters, ρ is fluid density, g is gravity acceleration and μ is a fluid viscosity

Fracture Spacing=Grid Block Size (one fracture per grid block)

Definition of Fracture Parameters in a Grid Block: III. Converting DFN Output to FCM Permeability



Example of DFN Realization of Fracture Network with 3 Fracture Sets



Summary of Methods: FCM (ELLIPSIM)

- An exact number of fractures can be generated.
- The fracture parameter distributions are not altered.
- The number of fractures can be very large.
- Ability for flow and transport through fractures and rock matrix
- Fractures are not explicitly modeled.
- Fractures are ellipses with fixed distribution of radius.
- Minimum fracture size is limited by the grid block size.
- Uniform orthogonal mesh is required.

Summary of Methods: FCM (SGSIM)

- No assumption regarding fracture shape is required.
- Aperture, spacing, and orientation are defined based on distributions of field observations (not calculations).
- The fracture parameter distributions are not altered.
- The number of fractures can be very large.
- An exact number of fractures cannot be generated.
- Fractures are not explicitly modeled.
- Minimum fracture size is limited by the grid block size.
- Uniform orthogonal mesh is required.

DFN-FCM Comparison

- **Direct Comparison: DFN versus FCM (DFN output)**
  - *DFN realization is converted to FCM realization - eliminates uncertainty in generating fracture network.*
  - *The only difference is between explicit (DFN) and effective (FCM) representation of fracture network.*
  - *Effective permeability of the modeling domain and breakthrough curves can be compared for each realization.*
- **Indirect Comparison: DFN versus FCM ELLIPSIM**
  - *Evaluates the difference in conceptual models – flow and transport through fractures (DFN) versus flow and transport through fractures and matrix (FCM).*
  - *Effective permeability of the modeling domain and breakthrough curves have to be compared based on statistics from multiple realizations.*

Test Case Fracture Parameters

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 radius R follows a truncated power law distribution:

$$R = R_0 \cdot \left[1 - u + u \cdot \left(\frac{R_0}{R_u}\right)^{\alpha}\right]^{-1/\alpha},$$

Fracture orientation Θ follows Fisher distribution:

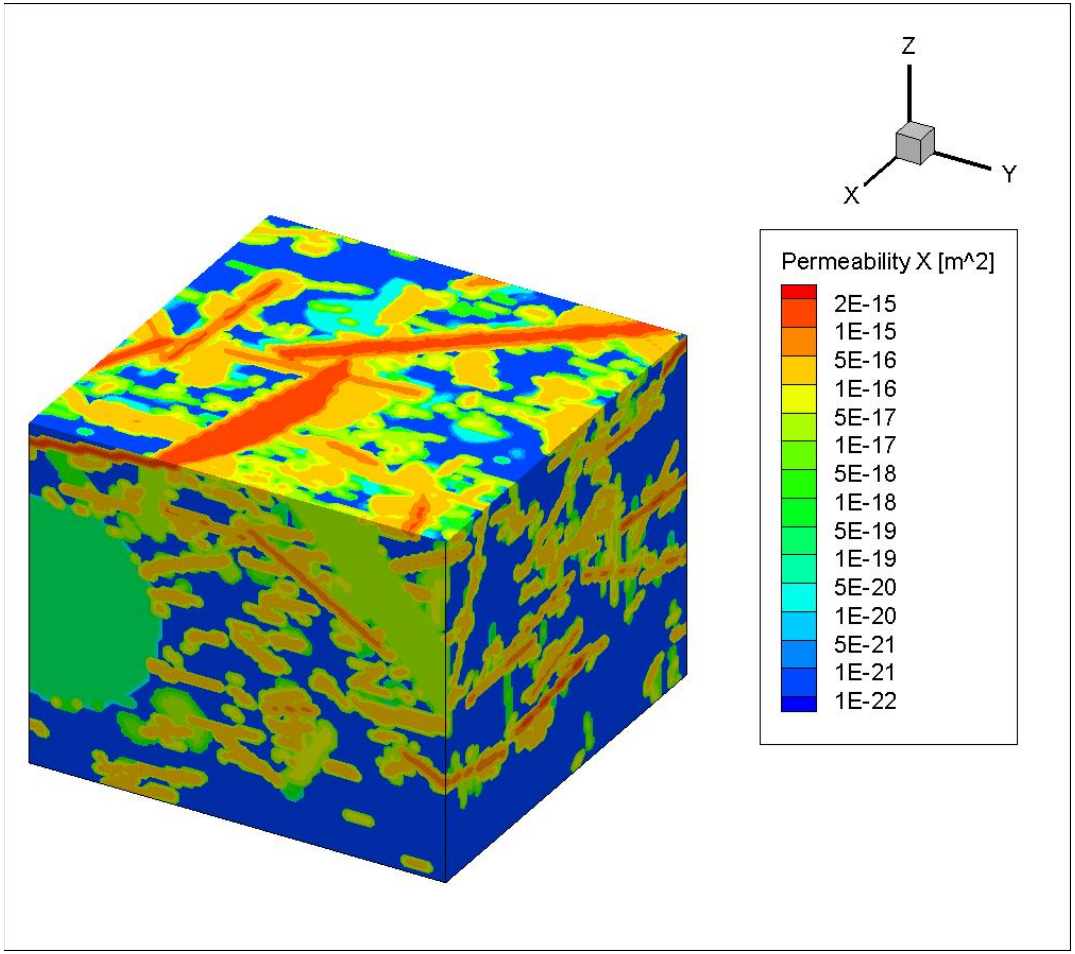
$$f(\theta) = \frac{\kappa \cdot sin\theta \cdot e^{\kappa \cdot cos\theta}}{e^{\kappa} - e^{-\kappa}},$$

Benchmark Simulations - Model Setup

- **Domain: 1000 m x 1000 m x 1000 m with cell size of: 10 m x 10 m x 10 m**
- **No. of Elements: 1,000,000**
- **Porosity: 0.01**
- **Permeability: Anisotropic (based on DFN output)**
- **Initial Conditions: Hydrostatic pressure**
- **Boundary Conditions:**
  - Pressure at West Face: 1.001 MPa
  - Pressure at East Face: 1.0 MPa

Anisotropic Permeability Field Based on DFN Works Output Data

- **5 Realizations (Permeability fields)**
  - Permeability field of Realization 1 shown



Effective Permeability Evaluation

- PFLOTRAN numerical simulator used
- Steady state flow utilized to estimate effective permeability for each realization
- Darcy's law and east face flux used to calculate effective permeability

Realization	Pressure Difference (Pa)	East Face Flux (kg/s)	Effective Permeability (m^2)
1	1000	4.57E-05	4.67E-17
2	1000	3.88E-05	3.97E-17
3	1000	4.15E-05	4.24E-17
4	1000	3.60E-05	3.68E-17
5	1000	3.79E-05	3.87E-17

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