$Aperture = A_{min} + (A_{max} - A_{min}) * p * \frac{L_{frac}}{(1+L_{frac})}$

Effective properties of multi-scale fracture networks

Ankesh Anupam, Nitish Konduru and Sanjay Srinivasan, The University of Texas at Austin

Abstract

Realistic representation of DFN on field scale simulation models have been impossible to achieve due to two reasons. Firstly, the representation of extremely large number of fractures and subsequent flow simulation is extremely computer intensive and secondly, the inability to represent fractures on the simulation grid,.

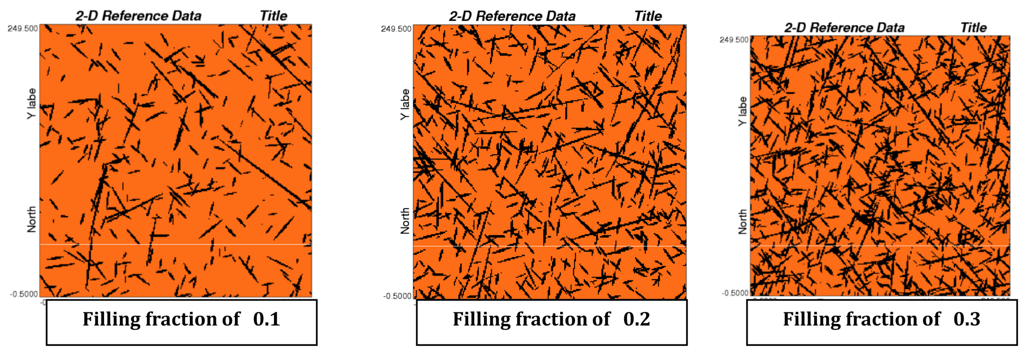
A hierarchical approach for fracture modeling and a novel random walker simulation to upscale the fracture permeability was attempted. The modeling approach entails developing effective flow characteristics of discrete fractures at micro and macrofracture scales without explicitly representing the fractures on a grid. The advantage of this methodology is that the upscaling process is extremely fast and works on the actual fractures with realistic apertures on a continuous space framework.

Introduction

The objective was to effectively characterize the flow in a naturally fractured reservoir. It is important to point that the permeability of a fractured system is not only a function of the degree of fracturing but also on the intersection characteristics of the fractures. There can be enormous differences in permeability for the same amount of fracturing but corresponding to different fracture pattern characteristics. This leads to uncertainty in the fracture network due to scarcity of the available data, as well as uncertainty due to the effective upscaled permeability. The primary research objective was therefore to represent the total uncertainty in the permeability field at the field scale using an effective and computationally inexpensive method.

Separate models were made for micro scale and macro scale fracture distribution with inputs from the seismic data and field observations. The micro-fracture model captures the sub grid fractures and subsequently use the map of regions affected by diagenesis to provide more reliable representation of aperture variations.

In order to assimilate this model for the microfracture in original field scale model it is necessary to calculate equivalent properties of the microfracture model.



Method

A random walker simulation is used that moves walkers along implicit fractures honoring the intersection characteristics of the fracture network. The random walker simulation results are then calibrated to high resolution flow simulation for some simple fracture representations. The calibration enables to get an equivalent permeability for a complex fracture network. These permeabilities are then used as base matrix permeabilities for random walker simulation for macro fractures. These are again validated with the simulator to get equivalent upscaled permeability. Several superimposed realizations of micro and macrofracture networks enable us to capture the uncertainty in the network and corresponding uncertainty in permeability field.

A random walker approach was chosen since that does not require explicit flow simulations and also can be used to take into account the influence of micro-scale fracture apertures.

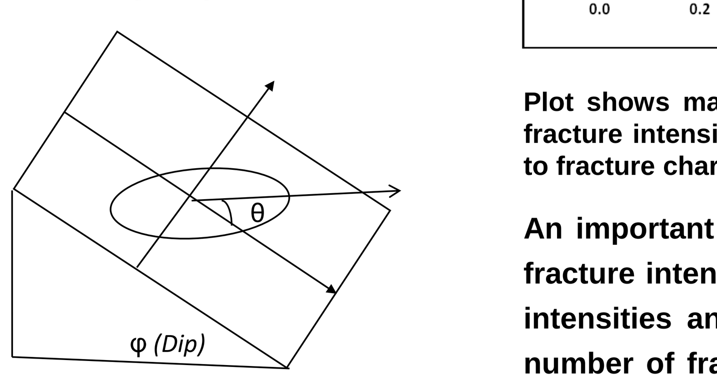
- Matrix and fracture permeability and the number of random walkers to simulate are user inputs.
- Random walkers placed on one of the faces of the microfracture model.
- A constant potential field is introduced between the face containing the walkers and the opposite face. Other faces are kept at a potential difference which varies periodically in a sinusoidal manner. This ensures that although the primary direction of the movement is fixed over a long time but the in situ direction of movement changes with time to time.
- Probabilities associated with each path of walker is computed.

Random walk simulation on a regular grid with realistic fracture apertures is impossible. Need to modify random walk simulation to take into account the fractures as elliptic planes with very small apertures and whose spacing, azimuth, dip etc. follow the earlier statistics. Fractures are being represented by ellipses in 3D with thickness equal to the aperture

$$\frac{\left((X-Xc)Cos\theta-(Y-Yc)Sin\theta\right)^2}{a^2Cos^2\varphi}+\frac{\left((X-Xc)Sin\theta+(Y-Yc)Cos\theta\right)^2}{b^2}=1$$

where

θ = 90 – Azimuth of the Ellipse
φ = Dip of the ellipse
(Xc,Yc,Zc) = Centre of the ellipse



Implicit Random Walker Simulation

Random walkers used in a un-gridded fracture domain. The algorithm implemented is:

- Find if walker is on a plane containing the ellipse/fracture (given azimuth and dip)
- Find if the distance of walker from the plane is less than the fracture aperture
- Test if walker lies on the ellipse of the fracture
- Check if walker is at a fracture intersection

WORK FLOW

- Define Fracture Intensity
- Simulate Fracture Network
- Use random walkers to analyze percolation
- Perform analysis on multiple realizations
- Do the same with different Fracture Intensities

At the start random walkers placed on one of the faces of the domain. Then they are moved along the fractures using connected paths and reaching the intersection points between the fractures. If even a single particle is able to reach the other end we can say that the network is percolating.

Microfracture modeling

Microfractures can be defined as small scale, sub seismic fractures extending within a grid block. Nevertheless it is important to model these microfractures, because of their influence on the effective permeability of each grid block. A single flow simulation grid block is divided into 100x100x100 grid blocks in order to represent the microfractures. The size of the domain is big enough to contain sufficient number of microfractures to have a statistically stable distribution of fractures.

Fracture Property Generation

Fracture Centre
The centre of fracture (Xc ,Yc ,Zc) is generated randomly within the domain implying that there is no spatial preference for micro fractures within the simulation grid block.

Fracture Length
The length of the fracture is the length of the major axis of the ellipse. The length distribution follows a power law distribution with an exponent of 3.1. The maximum length of the microfracture will be half the length of the domain size. This ensures that all the fracture generated lie within the domain (grid).

Dip and Azimuth
Both of these parameters are assumed to follow a normal distribution.

Aperture
The aperture is picked from a uniform distribution with a linear dependence on length of the fracture. The following relation is used for the fracture aperture.

$$Aperture = A_{min} + (A_{max} - A_{min}) * p * \frac{L_{frac}}{(1+L_{frac})}$$

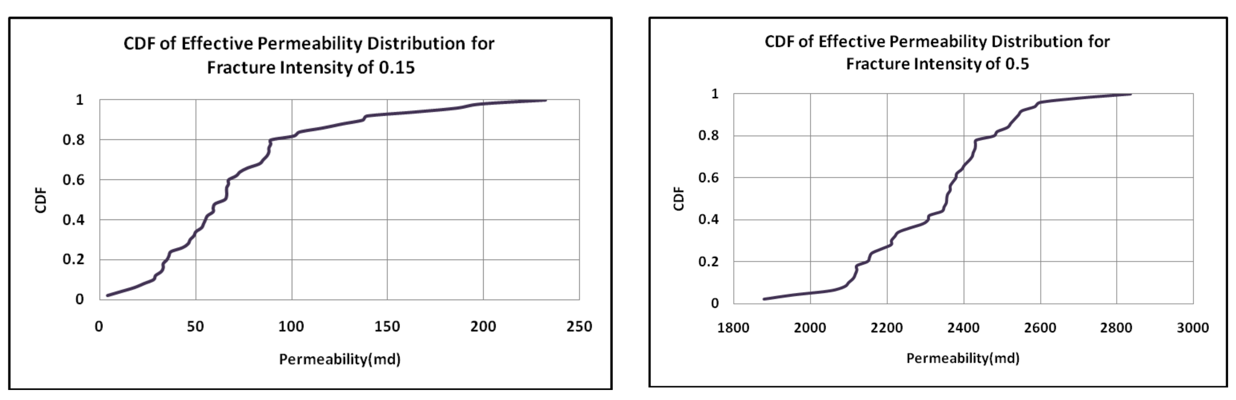
Where,
A_{min} = Minimum Aperture
A_{max} = Maximum Aperture
L_{frac} = Length of Fracture
p = Random number (0, 1)

The maximum and minimum aperture values are based on some of the observed fracture apertures in cores. The maximum value is around 2-3mm while minimum value is 1μm.

Fracture Set Generation

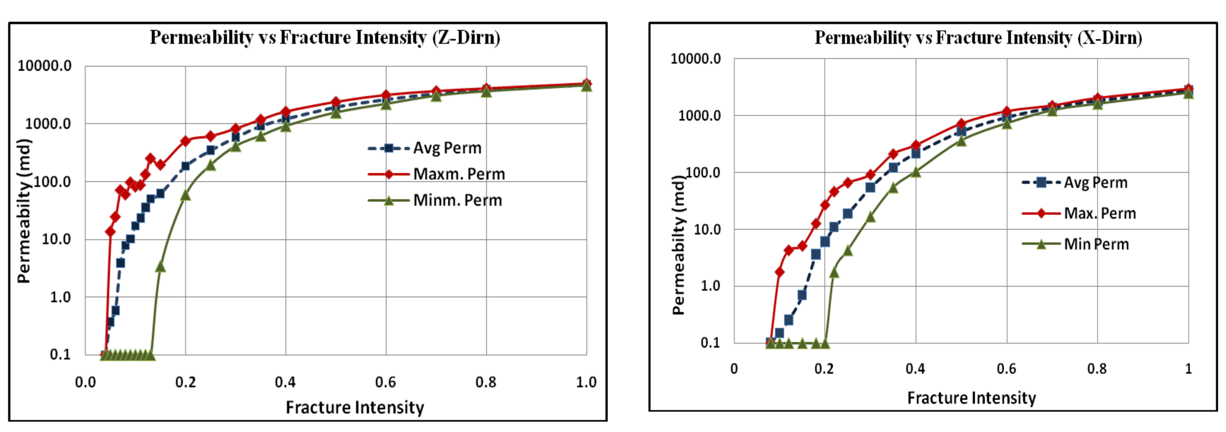
At the sub-seismic resolution, it is assumed that generation of new microfractures is independent of prior existing microfractures. And therefore the generation of a new fracture set is independent of any prior existing fracture sets. This allows microfractures to be able to cut across each other without any restrictions and form a 3-D fracture network for fluid flow.

Results



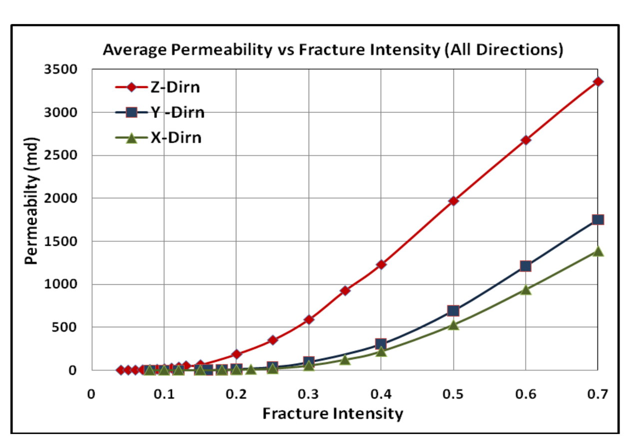
Cumulative Distribution Function of permeability for fracture intensity of 0.15 and 0.50. The plot shows the permeability uncertainty arising due to different fracture patterns. The ratio of maximum to minimum permeability is much lower corresponding to a fracture intensity of 0.5.

Percolation study has been performed on microfractures in all the three directions to quantify the permeability anisotropy of the system.



Plot shows maximum, minimum and average upscaled permeability corresponding to each fracture intensity value for flow in the z and x-directions. The uncertainty in permeability due to fracture characteristics is indicated.

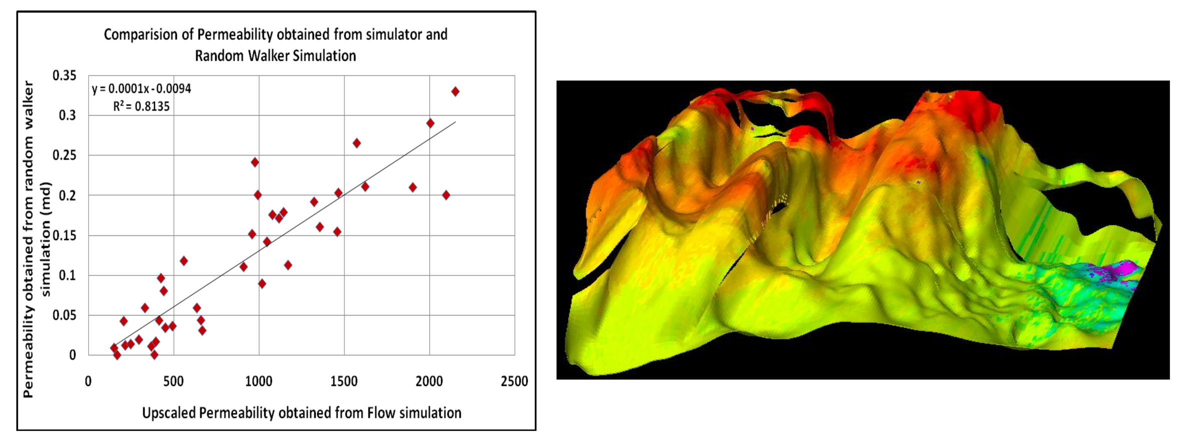
An important point to note is that the variation in permeabilities is higher at lower fracture intensities and all the three permeabilities merge to a single point at higher intensities and remain constant with further increase in fracture intensity. As the number of fractures increase beyond a limit in a percolating medium, the effective permeability is limited by the maximum permeability of individual fracture and remains constant.



Variation in average effective permeability in three directions as the fracture intensity is varied. The permeability in z-direction is higher than that compared in X and Y directions.

Validation of Results

A validation study was attempted to verify the accuracy of the results obtained by percolation analysis. For this task, the commercial simulator (CMG) has been used. Different sets of fracture models with different fracture intensities were created. These models were created on a smaller domain exhibiting a simple fracture network. The models were intentionally kept small and simple to keep the simulator run time manageable.

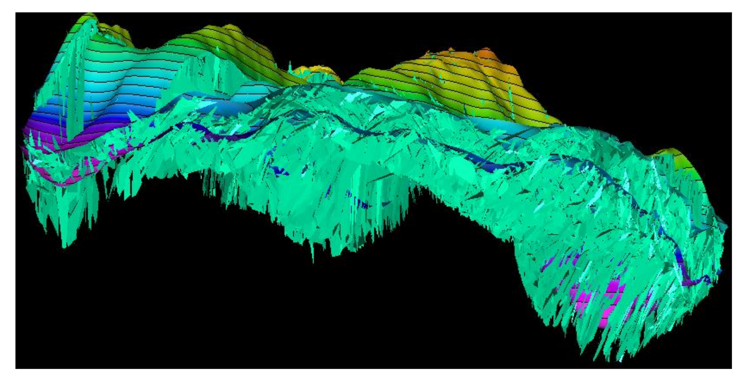


Comparison of upscaled permeability values calculated using the random walker to that obtained by applying flow based upscaling. Map of maximum upscaled permeability in the z direction computed using the random walker simulation. It can be clearly observed that the microfracture permeability is high near the anticlines where the fracture intensity values are high

Modeling macrofractures

Macrofractures defined as fractures that span more than one grid block. These are large-scale features that can sometimes be seen through seismic interpretation. The aim is to simulate macro fractures at field scale using fracture intensity as conditioning data. The distribution of macro fractures for each fracture set should comply with the fracture intensity map for a given fracture set. The other parameters that are input are power law distribution for the fracture length and normal distribution for the fracture dip and azimuth. Ellipses in 3-D with a finite realistic aperture are used to represent macrofractures.

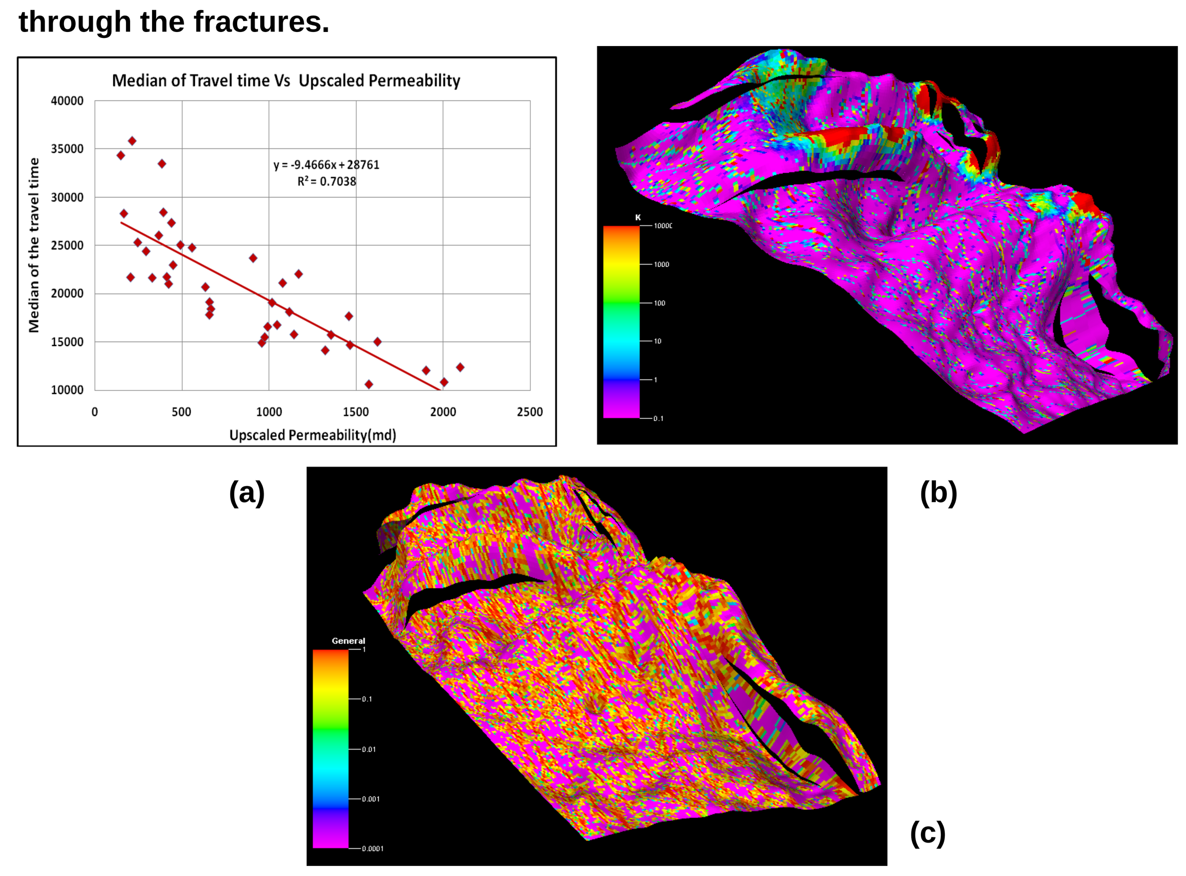
Six sets of macrofractures were generated. Each set is conditioned to secondary seismic/well information. The fracture intensity of the previous chronological set is used to condition the subsequent set in order to impose the correct hierarchy of fracture sets.



A realization of the macrofracture model showing the cross sectional view of the macrofracture model.

Random Walk Simulation

The ultimate objective of the random walker simulation is to find the upscaled permeability of fracture network integrating both the microfracture and the macrofracture models. Explicit representation of fractures at both scales is not possible given the wide range of length and aperture distributions. Therefore to incorporate the effect of microfractures, the upscaled microfracture permeability is used as matrix permeability when simulating the movement of particles through the macrofracture. With the introduction of finite permeability for matrix, the random walkers can now move through both fractures and matrix. This is unlike the random walker simulation used for upscaling microfractures where walkers could move only through the fractures.



a) Calibrating the median travel time of random walkers to flow based upscaled permeability. There exists a negative correlation showing that the travel time increases as permeability of system decreases. b) Final map of permeability in the x-direction. Since the fractures show an isotropic behavior aerially, this map also represents permeability in Y-direction. c) Map of interporosity flow parameter λ calculated using random walker simulation. Red areas highlight the areas where flow takes mostly through fractures.

Conclusions

- A hierarchical modeling approach on a continuous space domain was adopted. Hierarchical modeling of fracture entails generation of fracture models at two different length scales: microfractures and macrofractures. Using a continuous space domain, fractures are represented as elliptical discs with realistic apertures. Analytical equations of ellipse are used to represent the fractures and to determine their intersections.
- Microfractures are generated as elliptical discs scattered randomly in space with dip, azimuth and length following pre-specified probability density functions. Then on this implicit representation of fractures, the movement of random walkers are tracked and the percolation characteristics of the microfracture model is ascertained.
- The integration of micro and macro fracture models has been done by a continuous random walker simulation that now allows walkers to move through both fractures and matrix, with the matrix permeability being specified as the effective permeability corresponding to the microfracture network.

Acknowledgements

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