SAND2007-6480P

K-area Fracture Data: 2-D Simulations

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Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Goals of Simulation

- Create fracture models using K-area data that can be used as input to ground water flow model
- Examine sensitivity resulting simulations to input fracture parameters
- Results of interest:
  - 1) Resulting statistics of fracture sets
  - 2) Resulting percolation behavior of fracture sets
  - 3) Ground water flow and particle tracking

Review of Data: Boreholes

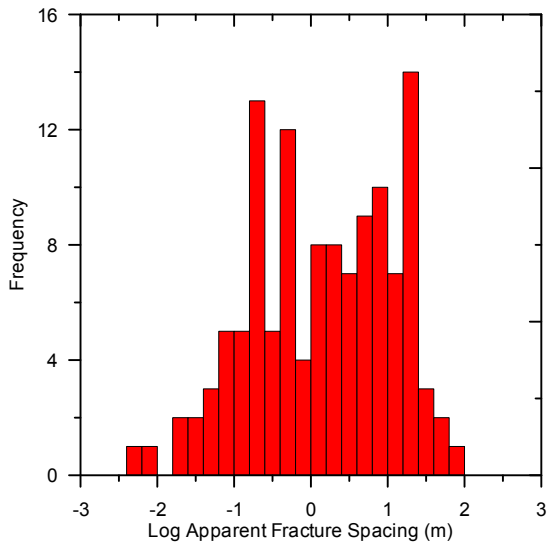
- 3 boreholes: KMBH 01, KMBH 02, KMBH 04
- Each one is 500m deep
- Data recorded
  - Location of fracture intersection
  - Azimuth
  - Dip
  - Width (mm)
  - Strike

Review of Data: Boreholes

- **Spacing**

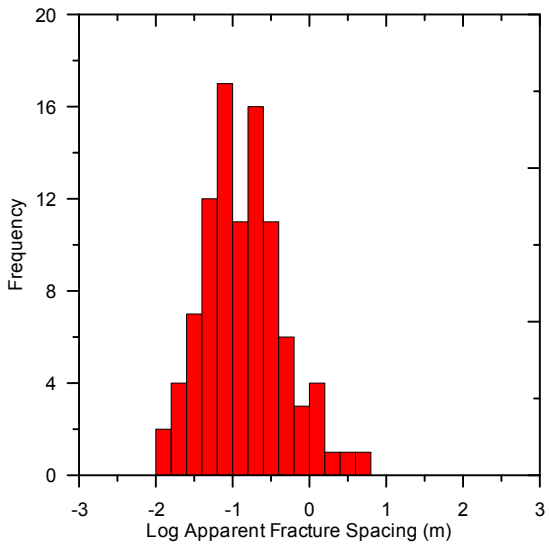
Background

KMBH01 + KMBH02 + KMBH04 (background)



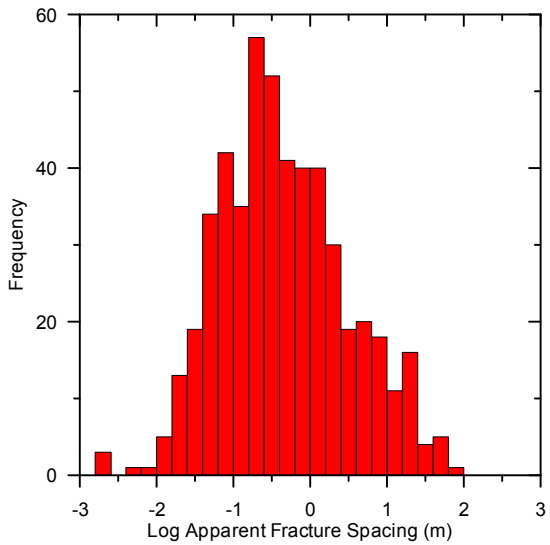
Fracture Zone

KMBH01 + KMBH02 + KMBH04 (fracture zone)



Combined

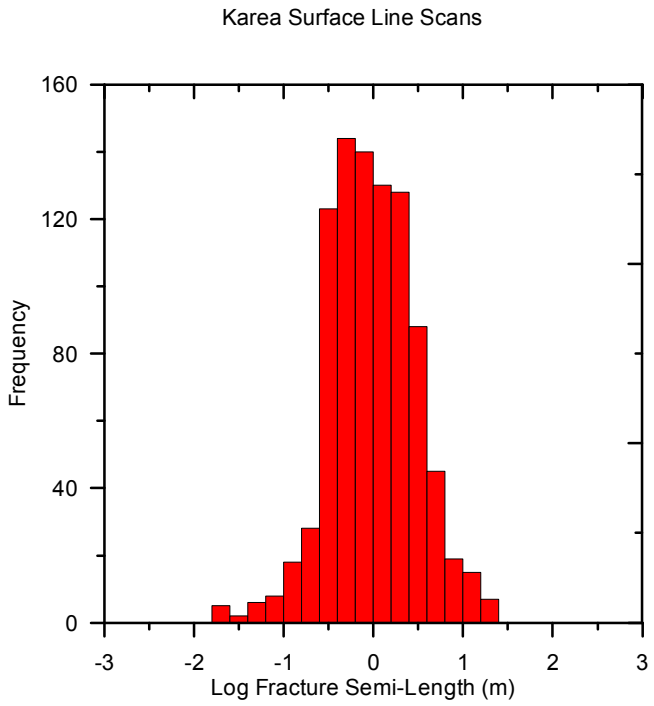
KMBH01 + KMBH02 + KMBH04



Some level of censoring on the low end is occurring. Limit of measurement seems to be between 1cm and 1mm

Review of Data: Pavements

- **Fracture lengths from pavements**



Data Review

- Distributions are fit to the different measured parameters.
- Conceptual model of Clustered Poisson fracture centers appears to be valid from available data
- These distributions serve as the basis for 2-D simulations of fracture networks

Summary of Data for Simulation

Set 1 (64%)	Distribution	Mean	Std. Deviation	Comments
Strike	Normal	N10E	30 deg	
Length	Log10 Normal	-0.02 m	0.48 m	
Spacing	Log10 Normal	-0.2 m	1.0 m	
Dip	Normal	61 deg	16 deg	Majority to SE
Set 2 (36%)				
Strike	Normal	N88E	16 deg	
Length	Log10 Normal	-0.02 m	0.48 m	
Spacing	Log10 Normal	-0.2 m	1.0 m	
Dip	Normal	58 deg	13 deg	60% to south
Fracture Zone				
Strike	Normal	N90E	46 deg	
Length	Log10 Normal	-0.02 m	0.48 m	
Spacing	Log10 Normal	-1.1 m	0.51 m	
Dip	Normal	50 deg	16 deg	90% to south

Simulation Approach

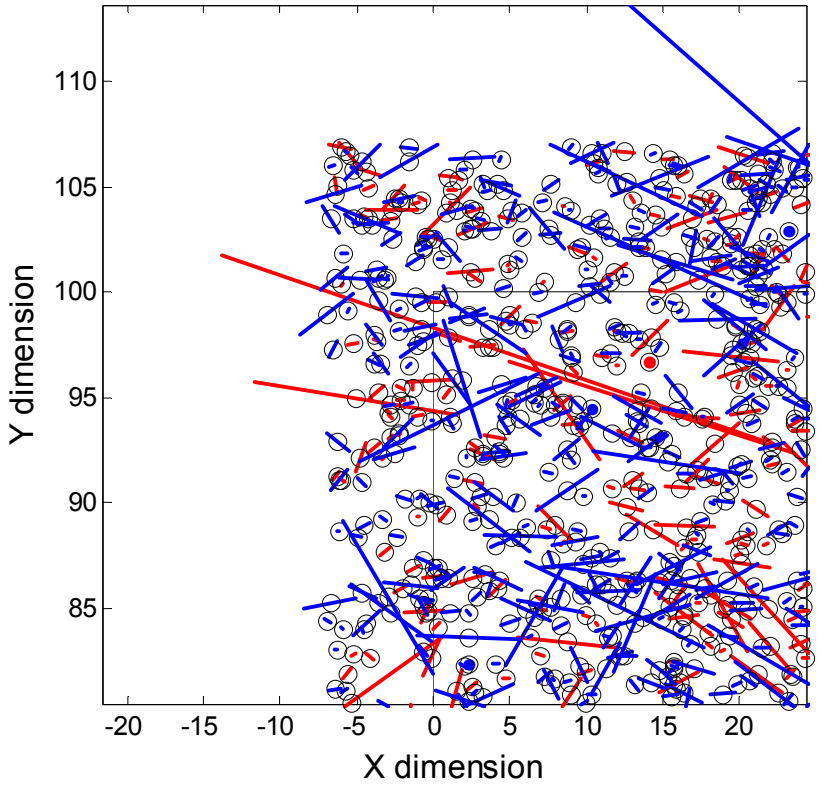
- Stochastic placement of lines in a 2-D domain
  - Draw from measured distributions on length and orientation
  - Consider spacing to be a resulting outcome and adjust total number of fractures to meet observed spacing distributions
- Limitations:
  - 2-D - dip orientations cannot be considered
  - No explicit consideration of intersections (e.g., termination probability)

Simulation Approach: Details

- Step 1: Determine simulation domain and buffer zone around the domain
- Step 2: Determine fracture set based on probability of occurrence
- Step 3: Simulate locations of the fracture centers
  - Poisson or clustered Poisson process
- Step 4: Draw lengths and orientations for each fracture
- Step 5: Remove fractures completely outside domain
- Step 6: Trim the ends of the fractures to fit within domain
- Step 7: Transfer to cell-based map (vector to raster)
- Step 8: Calculate cluster sizes and percolation characteristics

Simulation Approach: Details

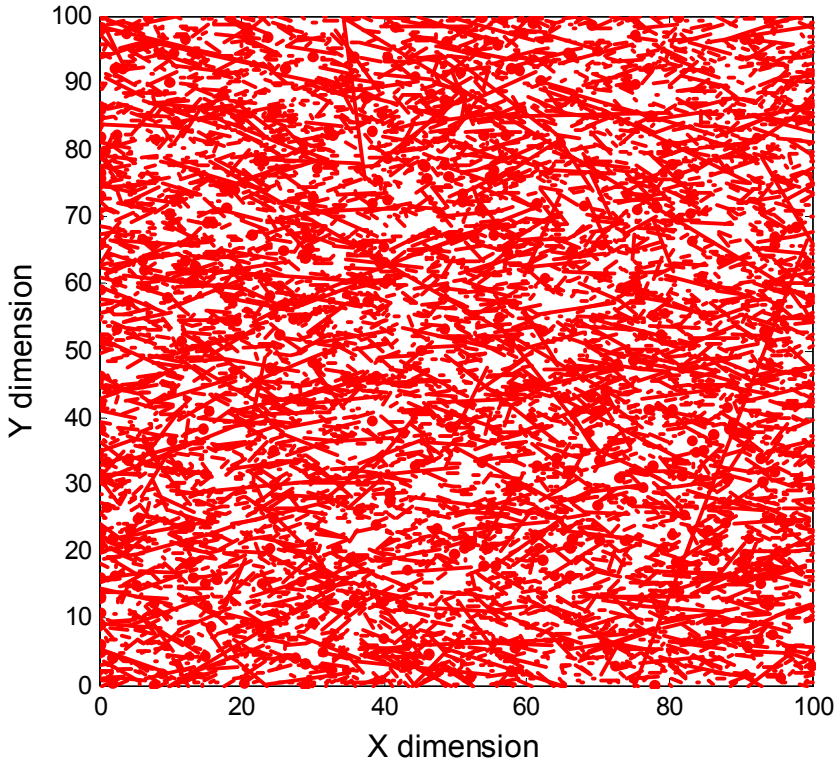
- **Two fracture sets (red and blue) each drawn from a different orientation distribution prior to clipping to domain boundary**



Note the simulation of fracture centers in the buffer zone outside of the domain boundary

Simulation Approach: Details

- **Example of a 100x100m domain with two sets of fractures, different orientations, after clipping to the domain boundary and removing fractures in the buffer zone**



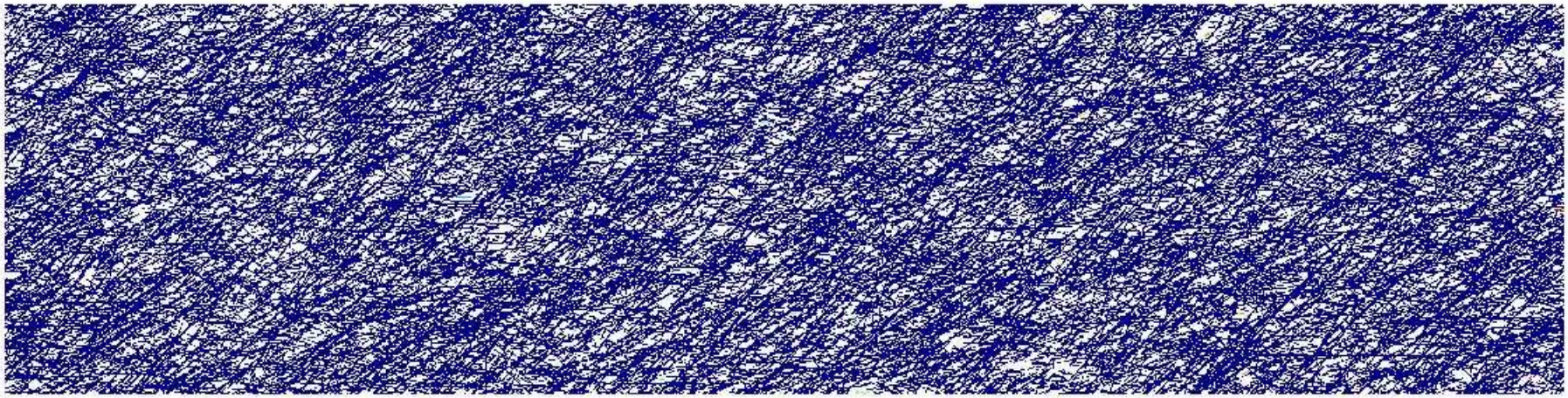
Tools for computational geometry:
http://people.scs.fsu.edu/~burkardt/m_src/geometry/geometry.html

Simulation Approach: 2 stages

- Simulate fractures as 2-D lines in space (vectors)
- Map fractures onto a cell-based grid (raster)
  - Cell grid is 10x10cm
  - Cells are either conductors or not depending on whether or not they are intersected by a fracture
  - For any fracture less than diagonal cell dimension, the cell containing that fracture center is classified as a conductor
  - Anisotropy of conductivity in cells is not taken into account – could be done

Example Fracture Network

- Example of a dense fracture network on a 10x10cm grid (200x50m domain)
- Expanded view of these networks shows that connectivity is maintained in the final grid
  - "stairstepped" appearance necessary to maintain continuity of vector quantities



Sampling the Network

- Resample the final simulated fractures to check on final representation of distributions
- Checking length and spacing
  - Length is more uncertain than orientation and subject to censoring at both the short and long ends
  - Spacing is not entered into the simulations explicitly, but is an outcome of the simulations and can be compared to observed spacing

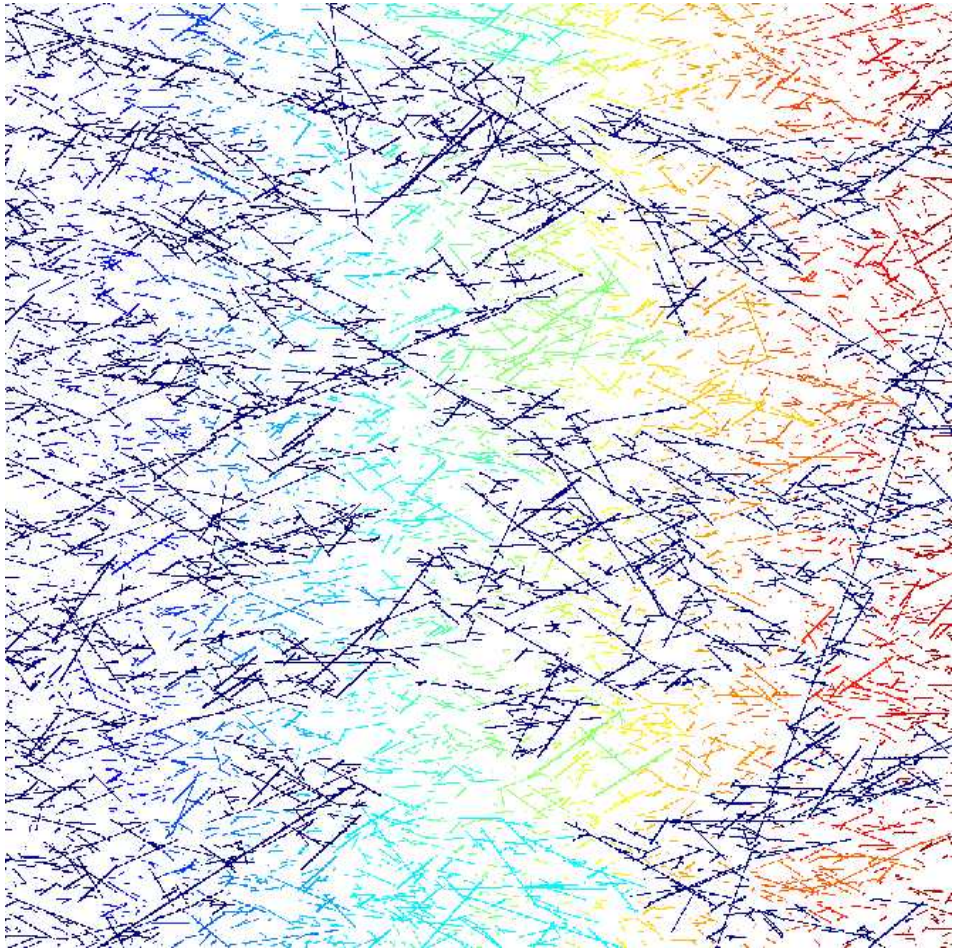
Sampling the Network: Length

- Lengths are drawn directly from distributions put together by Dr. Arnold
- Lengths are censored at the low end at log10 (-2.5) meters (0.0032 meters)
- Comparison is made for each network
  - Grab all simulated fracture lengths (all sets simulated here have the same length distribution)
  - Automatically fit a log-normal distribution to the lengths
  - Keep the mean and standard deviation of the best fit log-normal distribution for each simulation

Sampling the Network: Spacing

- For each fracture network:
  - Determine the equation of the line that is normal to the mean set orientation and passes through the center point of the domain
  - Extend this line from one edge of domain to the other (scanline)
  - Identify location of intersection point between this line and all fractures that intersect
  - Calculate one scanline for each set
  - Combine all spacings into a single data set
  - Automatically fit a log-normal distribution to the lengths
  - Keep the mean and standard deviation of the best fit log-normal distribution for each simulation

Example Fracture Network



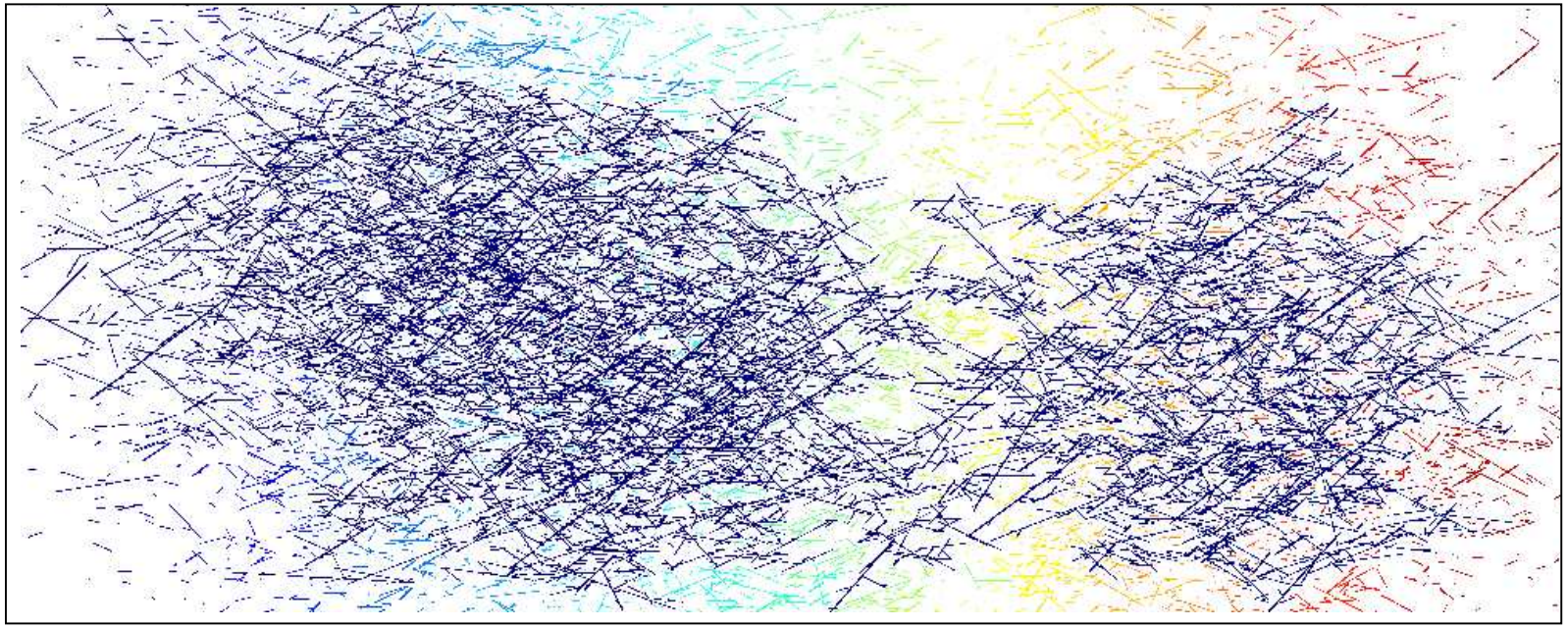
Square domain, 100x100 meters (1M cell model)

Single large cluster (dark blue) that has percolation in both the X and Y directions

Number of smaller clusters with a range of sizes throughout the network (other colors)

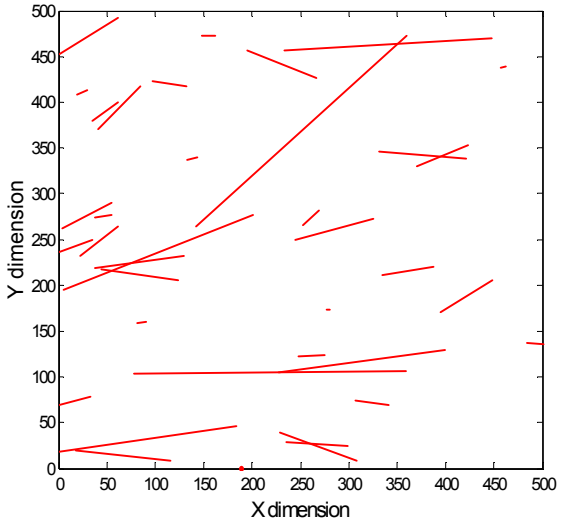
Example Simulations

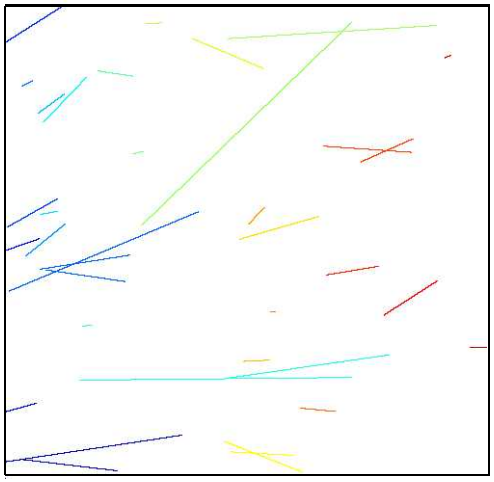
- Simulation with clustered Poisson conceptual model (2000x800 domain)
- Single large cluster has percolation in both X and Y directions



Fracture Network: Connectedness

Connectedness of fracture network dictates the amount of flow across the domain. Image on left shows locations of 40 individual fractures. Image on left shows 35 distinct clusters of connected fractures.



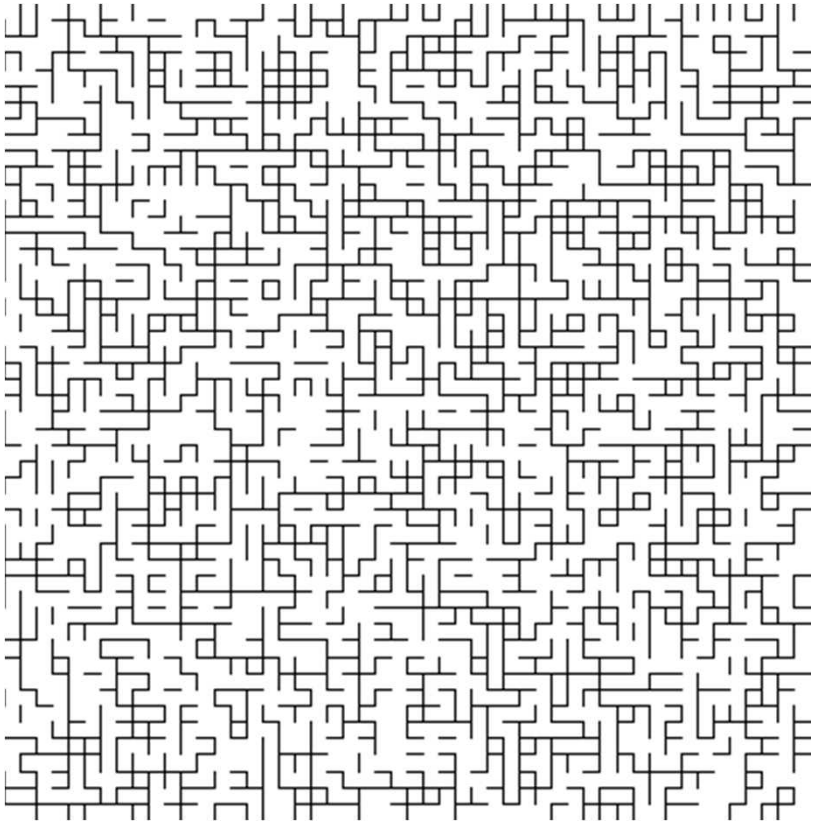


Percolation: Background

Development in statistical physics

Bond percolation on a square lattice where P(connect) is 0.51 for any given edge

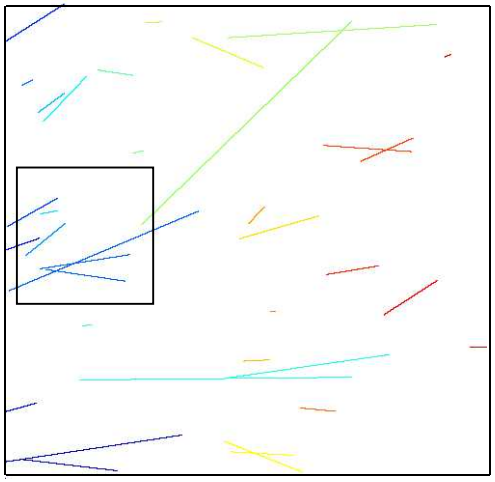
Percolation threshold is 0.50 for 2-D and approximately 0.249 For 3-D (square lattice with z = 4 and 6, respectively)



See: Sahimi, M., 1995, *Flow and Transport in Porous Media and Fractured Rock*, VCH, New York, 482 pp.

Percolation

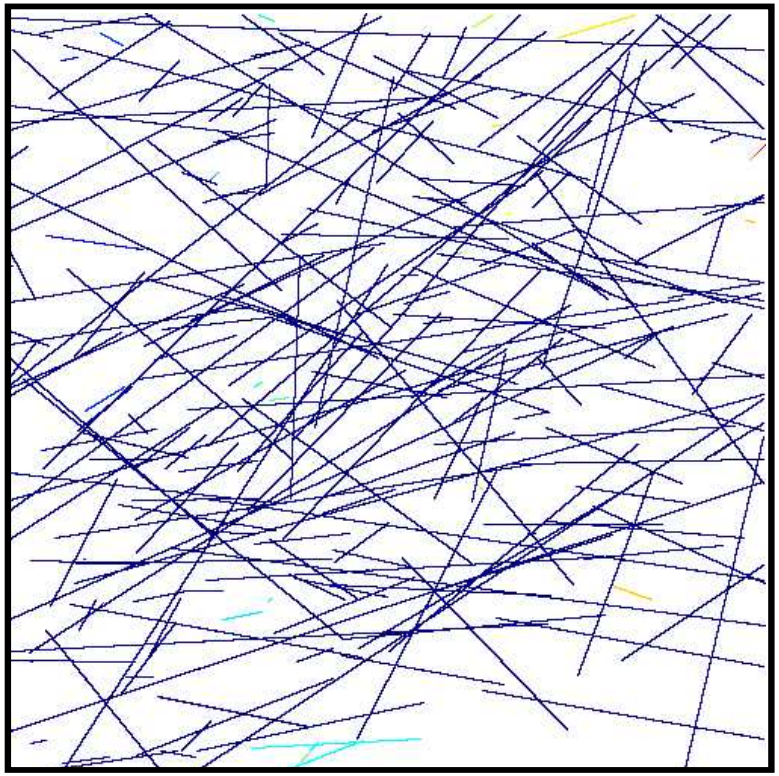
- Critical point at which the fracture network goes from impermeable to permeable
  - Network becomes connected across a volume
- Percolation only has definition within a *specified area/volume*



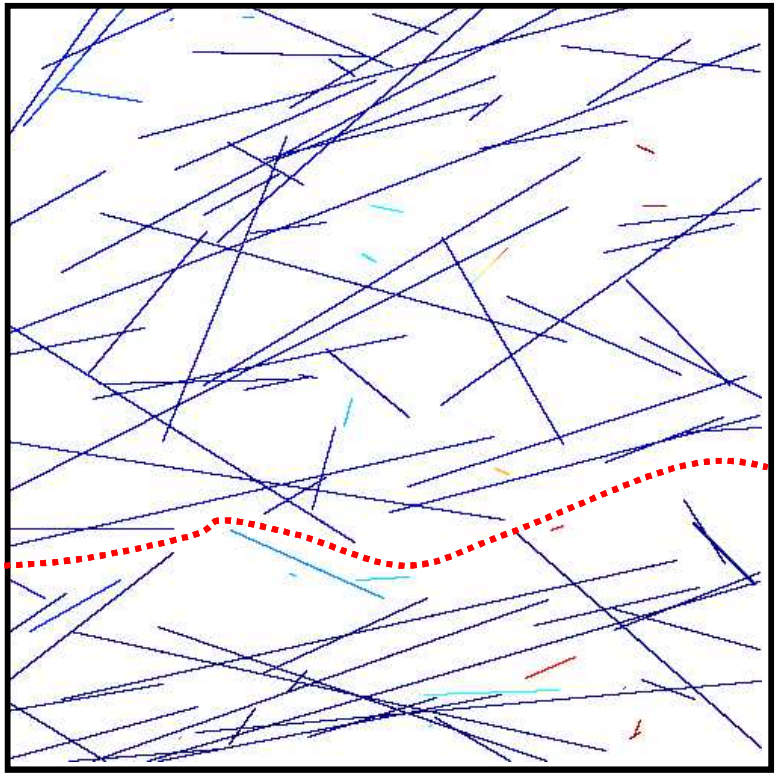
Percolation and Fractures

Fractures drawn from same length and orientation distributions

240 Fractures



100 Fractures



Pressure testing at Kamaishi mine

Simulation Sets

- 1) Simulations are done using a Poisson model only – no accounting for clustering of fractures
- 2) Simulations done with clustered Poisson model

- In both cases the total number of fractures is varied and the effect on the spacing distribution is monitored

Domain Size

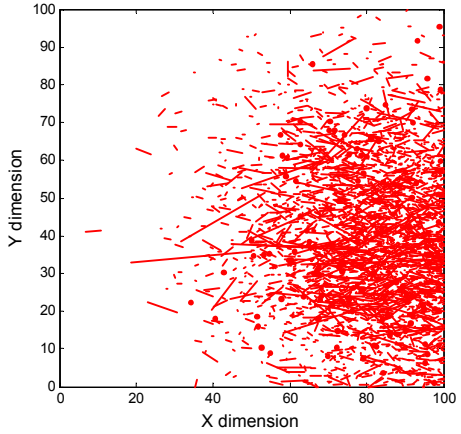
- Last March, used a 500x500 grid model (50x50m)
- Now using two different grids:
  - 1000x1000 (100x100m) for statistics and percolation studies (isotropic dimensions to determine preferred orientation of percolation)
  - 2000x800 (200x80m) for flow model (extend in the direction of the fracture zones and the flow direction in the K area)

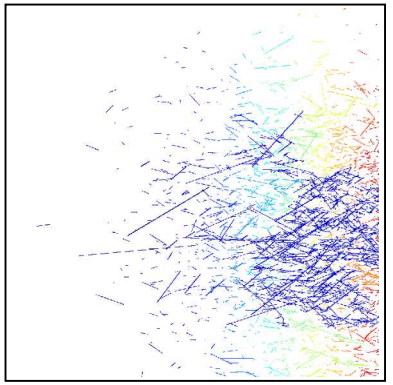
Results: Examples

- **Example Realizations**

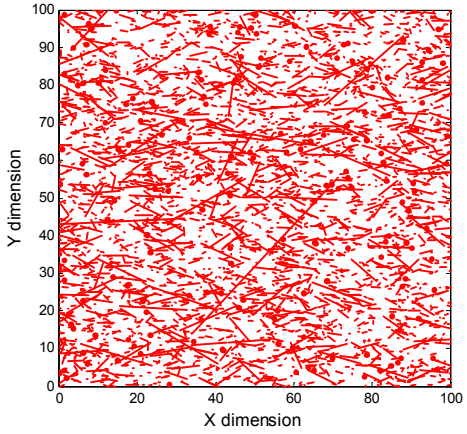
Colored by cluster

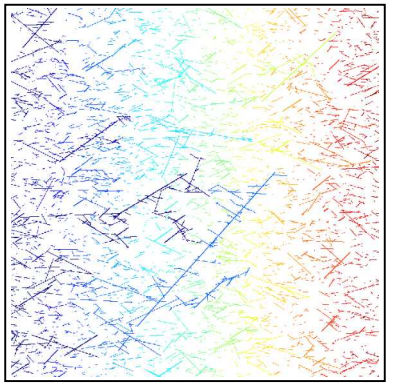
Clustering, 4500 original fractures





No clustering, 4500 original fractures

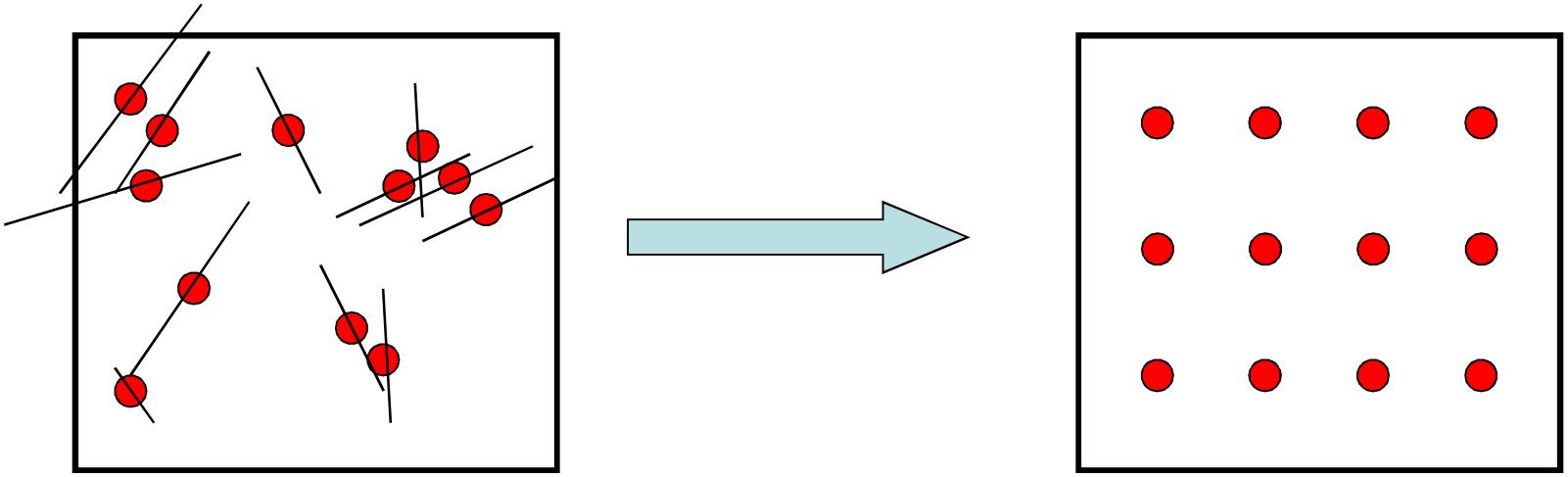




Fracture Density

- **Plot the following results as a function of the average distance between fracture centers if they were uniformly distributed**

$$FC_{dist} = \sqrt{Area} \,/\, \sqrt{N_{frac}}$$



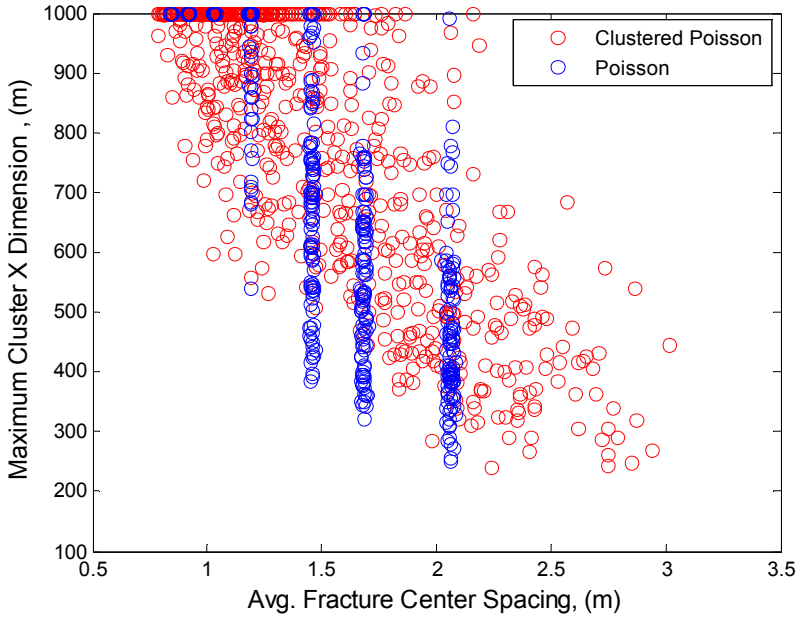
Conceptual Model Comparison

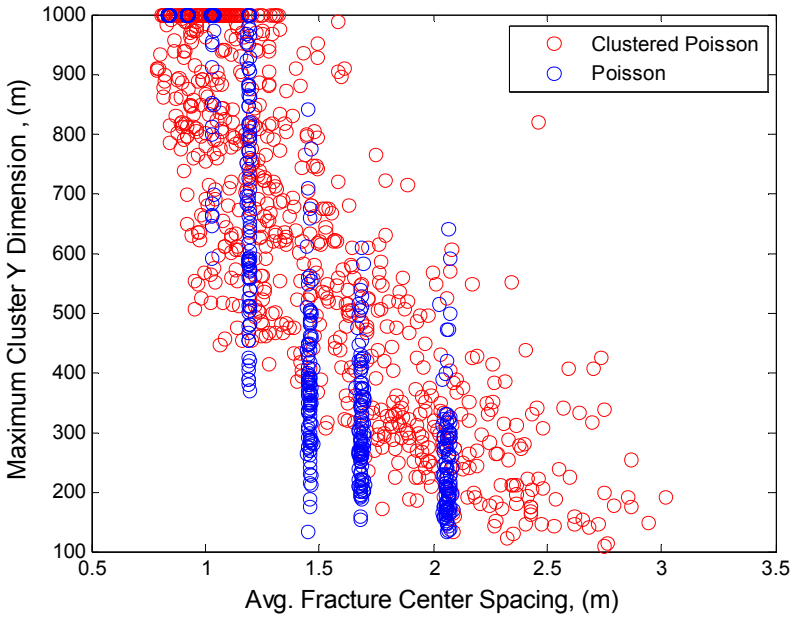
- Created fracture network simulations using two different conceptual models of fracture center placements:
  - Random (Poisson)
  - Clustered Poisson

- Compare resulting networks from the two models with respect to different statistical measures

Comparison: Max Cluster Dimensions

- **Maximum single cluster dimension (cells) in X and Y directions as a function of mean fracture center spacing**

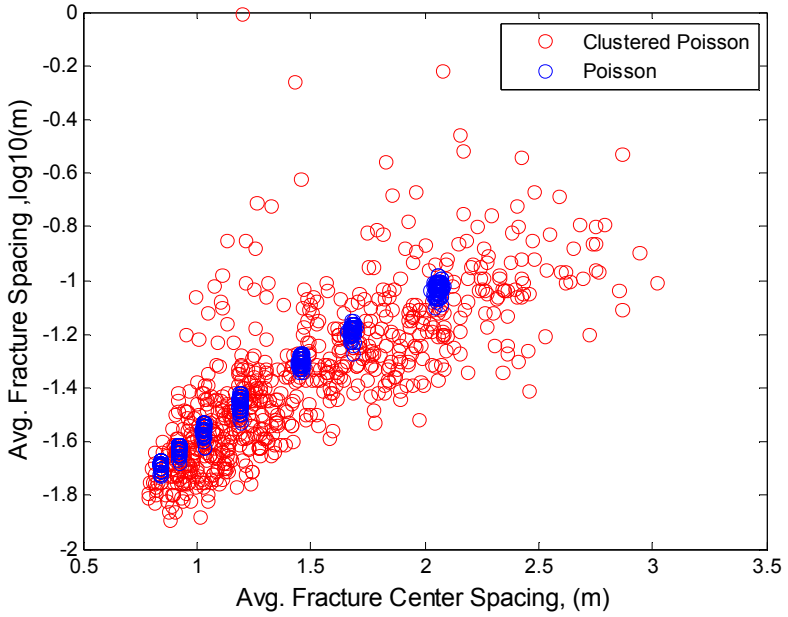


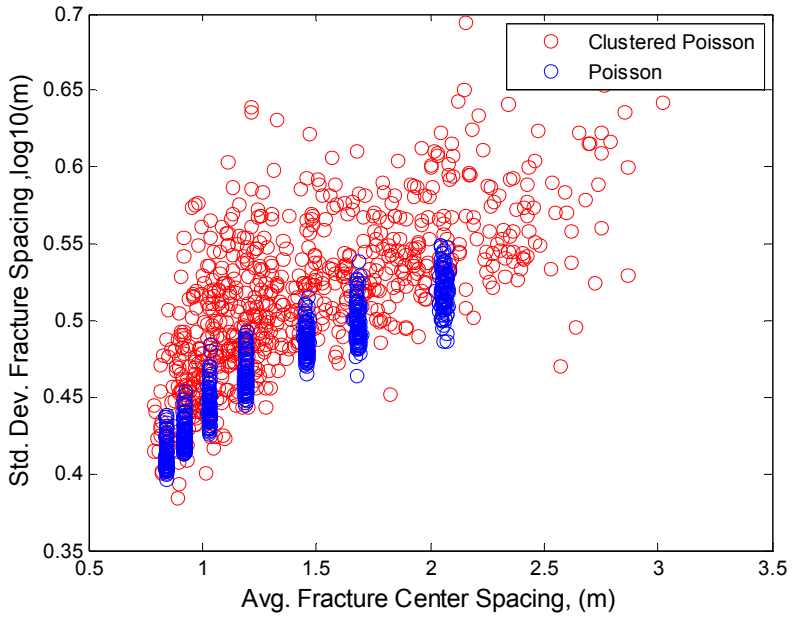


Maximum size is limited to the size of the domain: 1000 cells

Comparison: Fracture Spacing

- **Mean and standard deviation of fracture spacing. Both sets are combined in a single calculation**

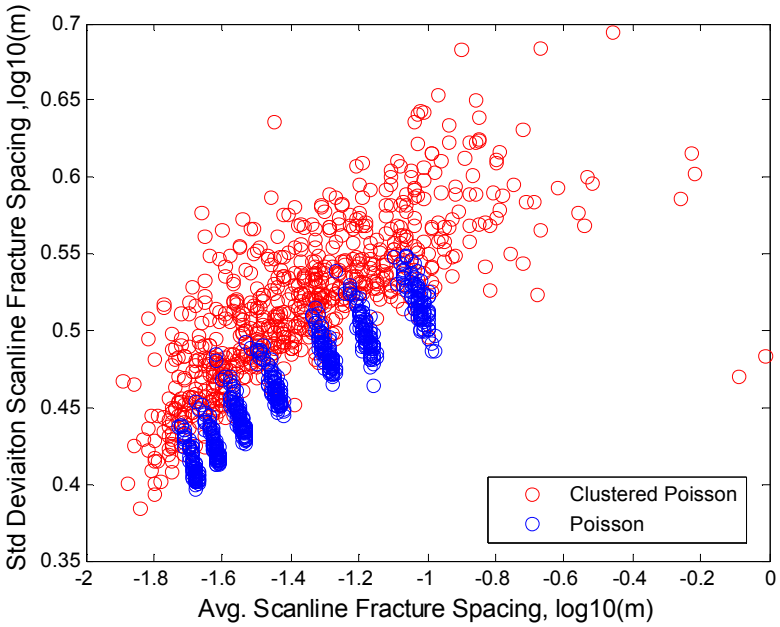




Spacing measurements are censored at the low end at log10 (-2.5m) (0.003m)

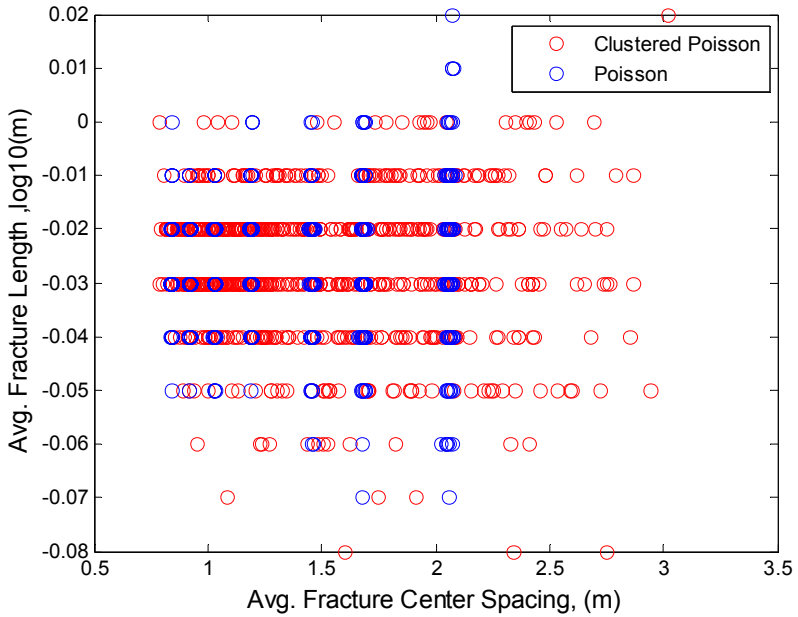
Measured Fracture Spacing

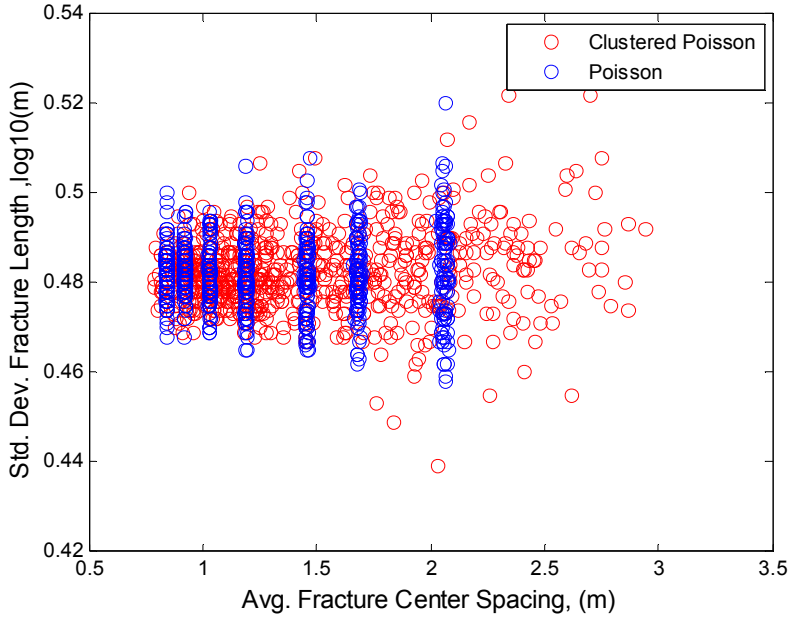
- **Can we get the measured log-normal distribution of fracture spacing?**



Comparison: Fracture Length

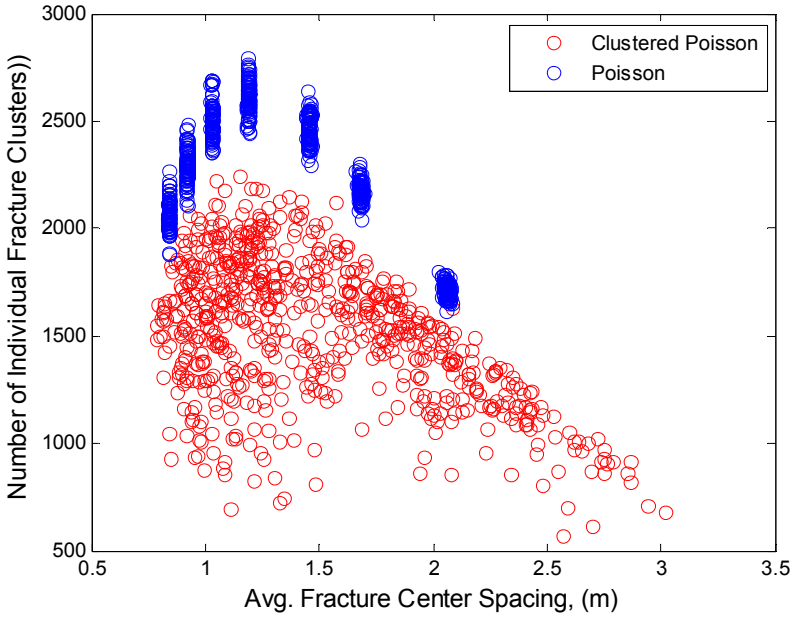
- **Mean and standard deviation of simulated fracture lengths**





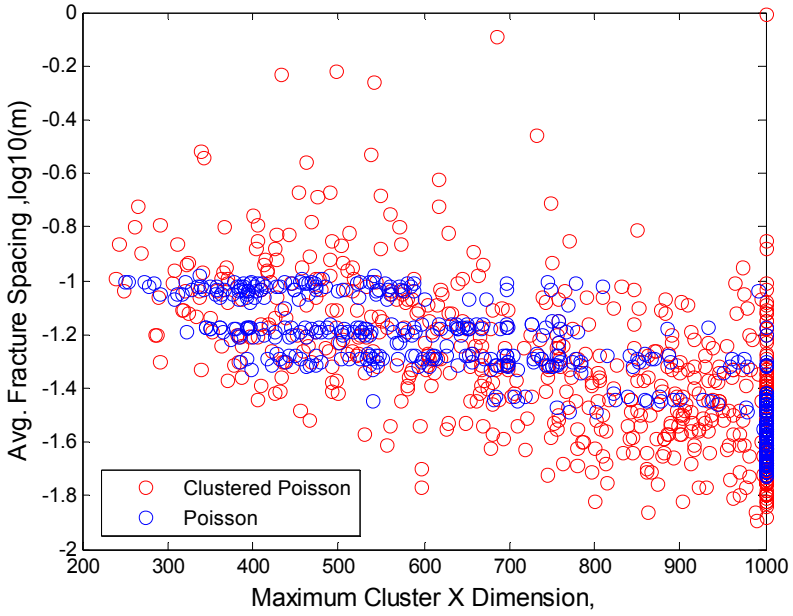
Comparison of Fracture Clusters

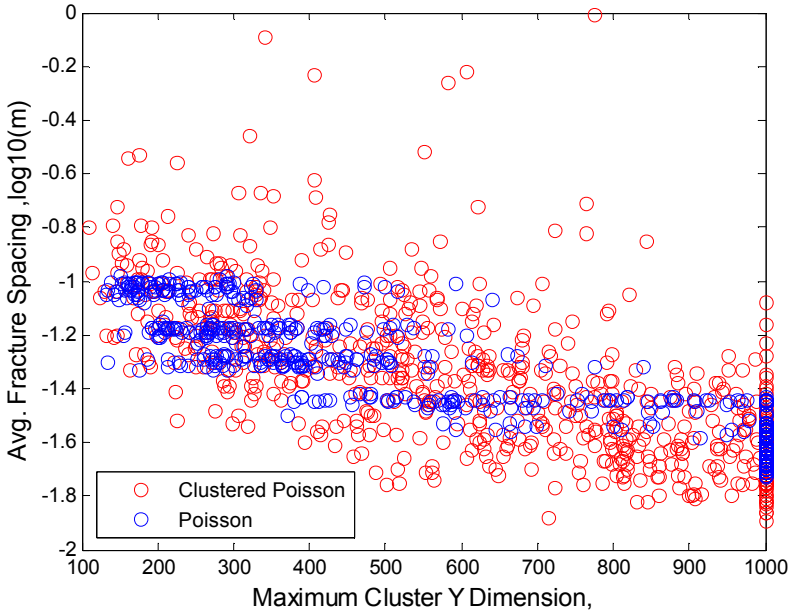
- **The number of individual fracture clusters as a function of average fracture center spacing**



Fracture Spacing vs. Cluster Size

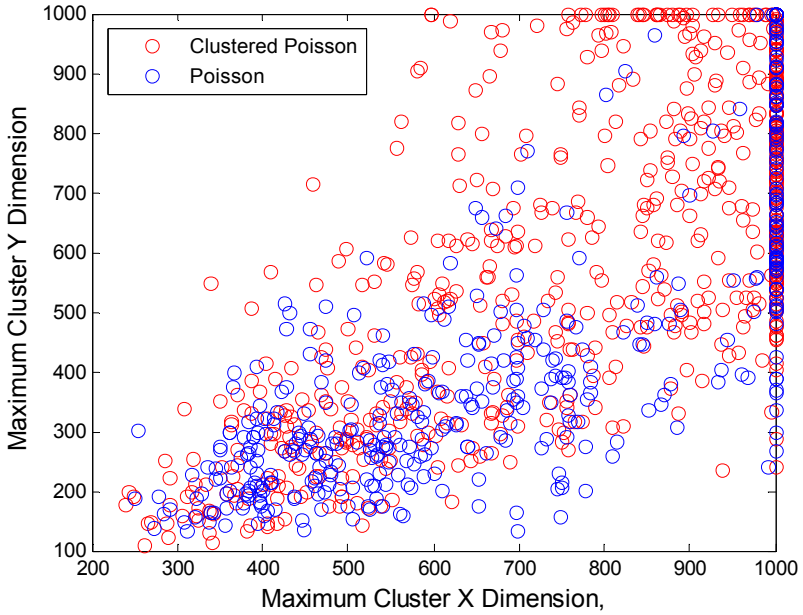
- **Can we get percolation and observed fracture spacing?**



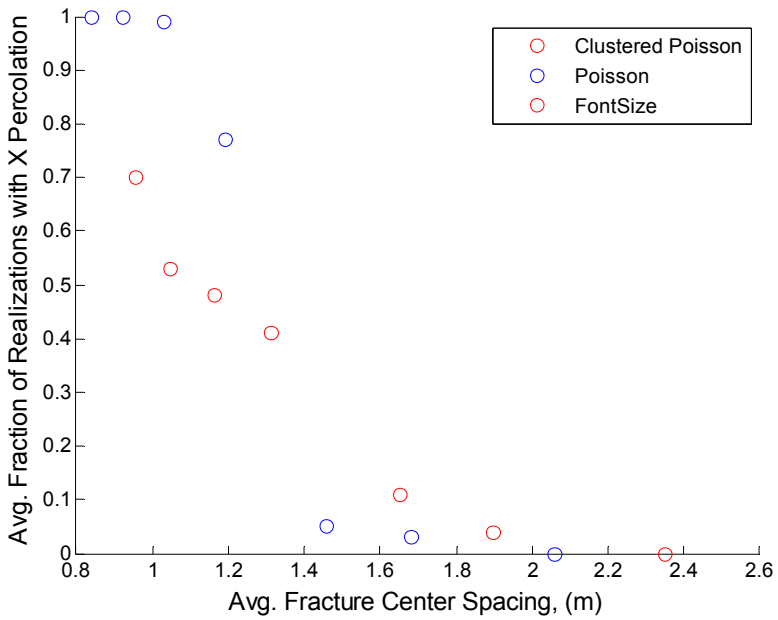


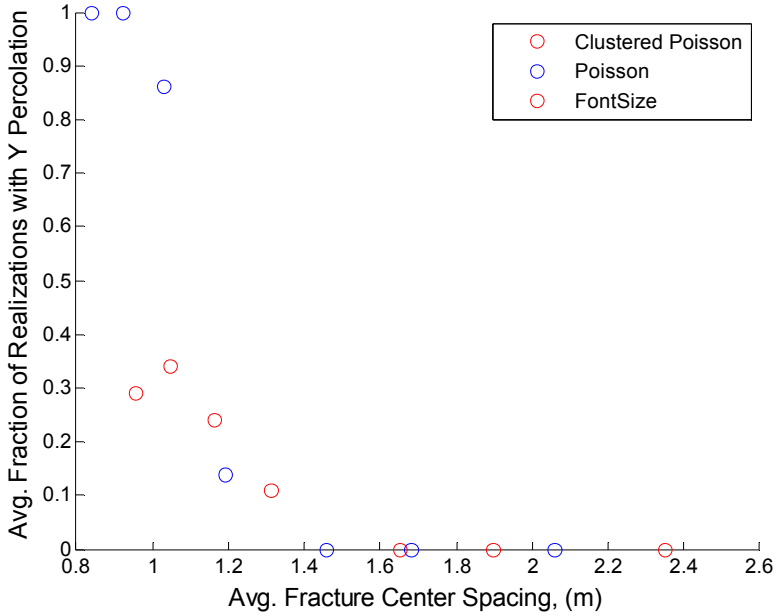
Maximum Cluster Dimensions

- **Almost all percolating clusters in Y direction occur under Poisson cluster model**



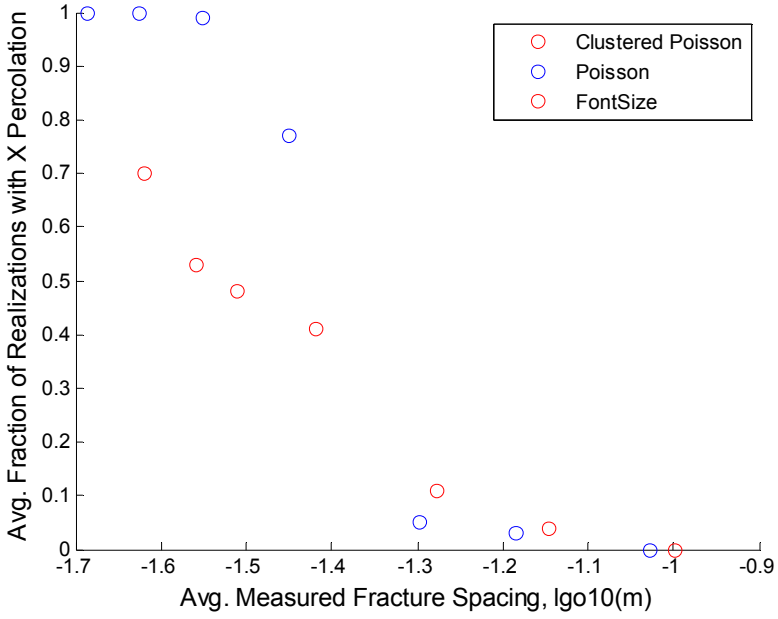
Comparison: Percolation Fraction

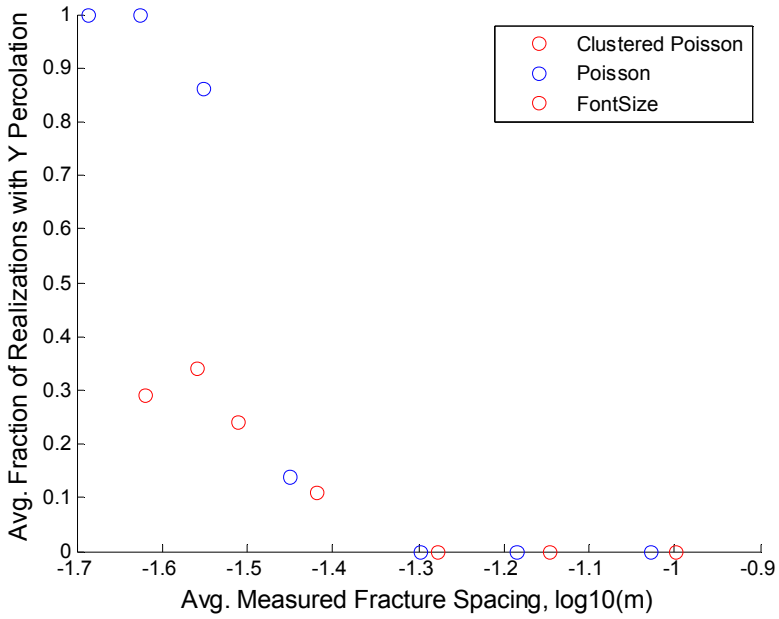




Measured Fracture Spacing

- **Percolation fraction as a function of the scanline measured fracture spacing**





Fracture Simulation: Summary

- For given number of fractures, greater probability of percolation in the X (east-west) direction than Y (north-south) direction
- More variation in nearly all measured properties for clustered Poisson model relative to Poisson model
- Fracture simulations do not adequately match the measured spacing distributions
  - Clustered Poisson model is closest
- Length distributions are well matched in simulations of both conceptual models

Ground Water Flow Simulations

- Change the domain shape and size for the ground water flow simulations
  - 2000x800 =1.6M cells (200x80 meters)
  - Based on higher probability of percolation in X direction than in Y direction
- Steady-state flow from west to east
  - No-flow boundaries on north and south
- Gradient = 10/200 = 0.05

Particle Tracking

- For each fracture simulation, one streamline is tracked from west to east end
- Starting location is at the center of a 20 meter long fracture (Y dimension) upstream end (10.5m) of domain
- Examine timing and tortuosity of streamline