Dispersion in small-scale discrete fracture networks with internal fracture roughness: Challenges for site-scale modelling

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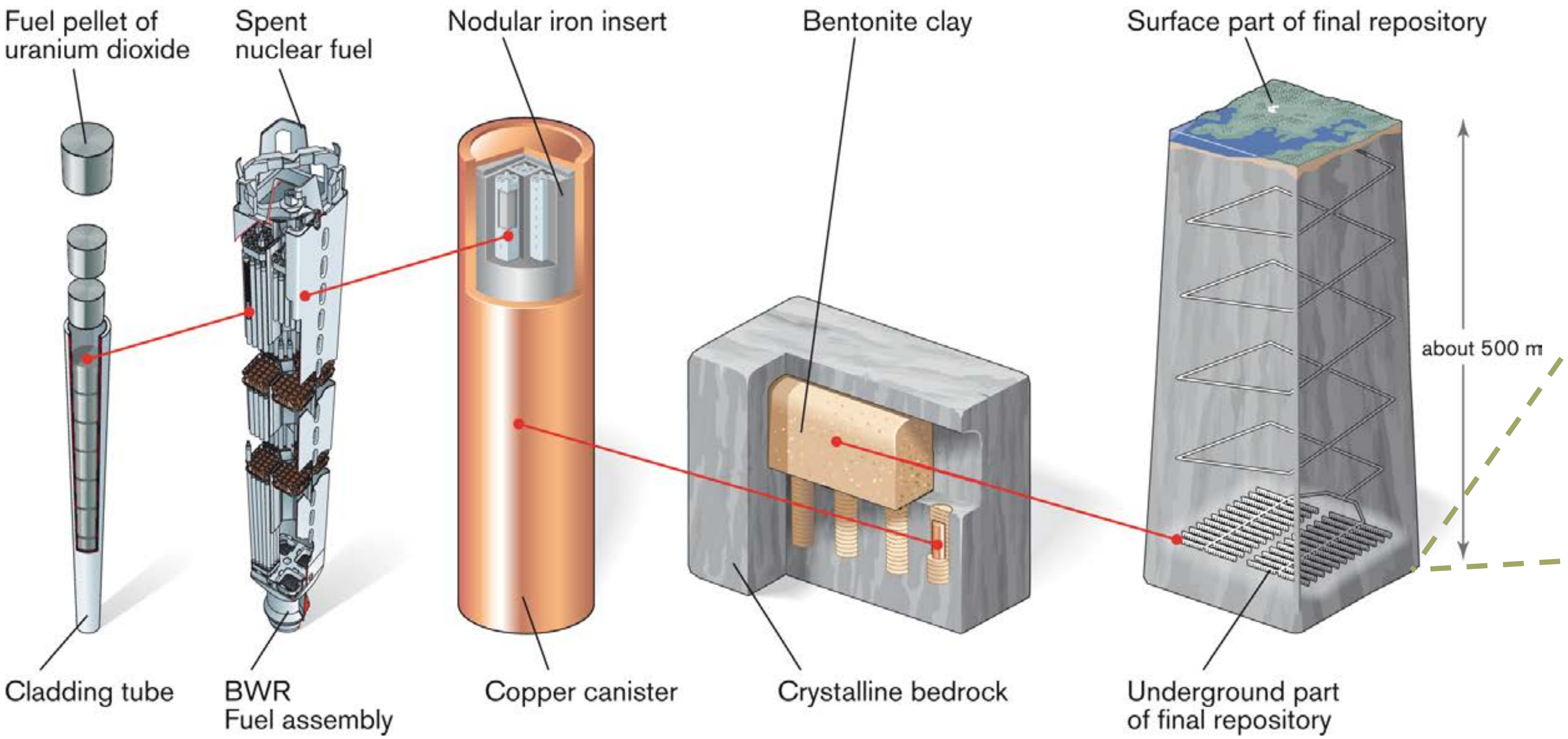
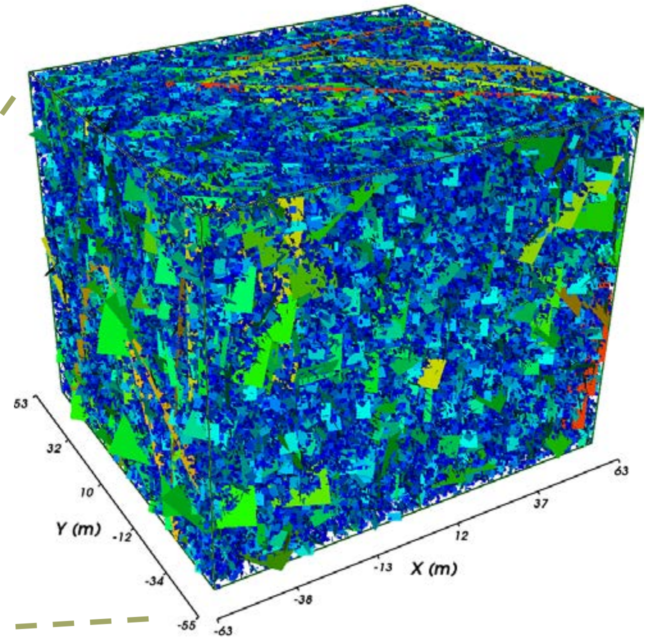
Background and motivation

- Application: Storage of spent nuclear fuel in sparsely fractured crystalline rock
- Discrete fracture network (DFN) models form critical part of safety analysis
- DFN models used to simulate flow and transport in sparsely fractured bedrock
- Stochastic DFN models typically based on fracture statistics obtained from field data and require many Monte Carlo realisations for robust analysis



Img: SKB, illustrator: Mats Jerndahl



- DFNs used to simulate flow and transport in fractured bedrock
- Forms critical part of safety analysis for final repository

Background and motivation

- Most DFNs simplify representation of fractures as smooth surfaces, as parallel-plates
- However, real-world fractures are rough, with significant variability in aperture

- Variable fracture aperture (roughness) is expected to impact dispersion
- Highlighted in review paper by Bodin, J., Delay, F., & de Marsily, G. (2003)*:

“For intermediate velocities, i.e., those observed in a fracture under natural flow, the solute spreading mainly results from the aperture variations”

“...the assumption that consists in neglecting the “microdispersion” of single fractures is questionable, particularly when dealing with pollutant transport”

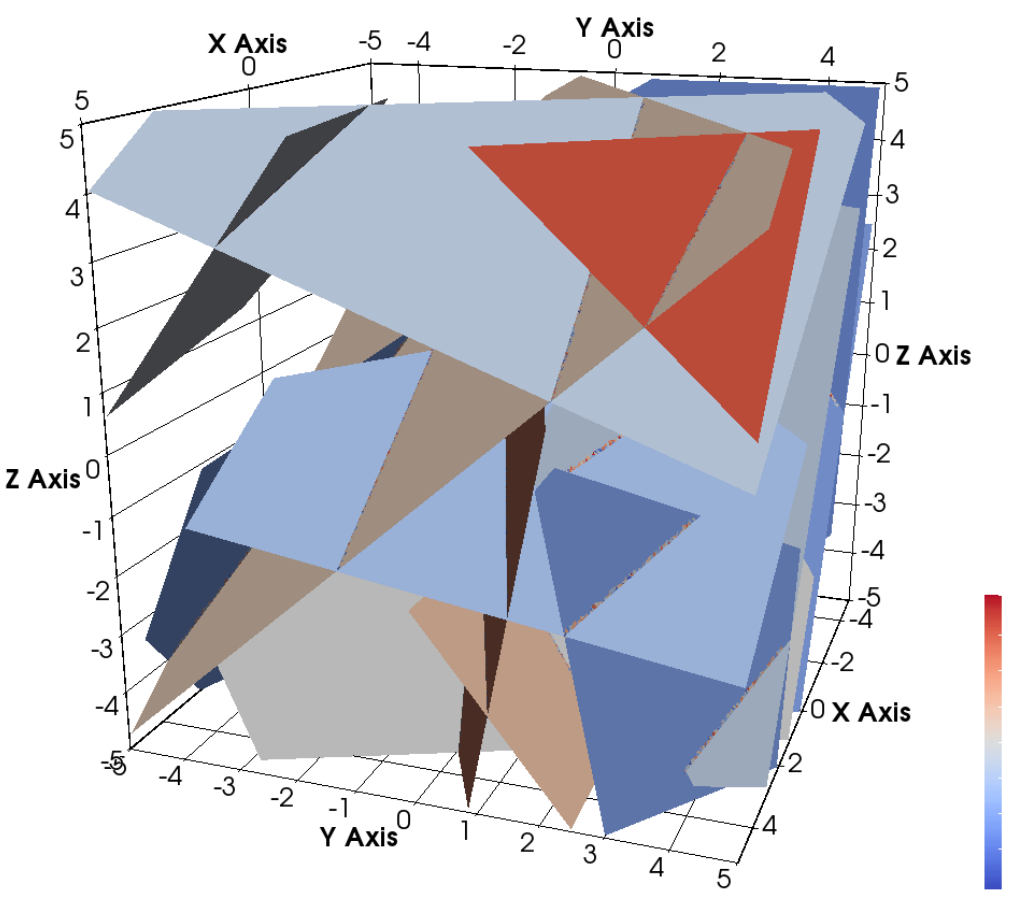
“Therefore, microdispersion should not be neglected when dealing with radionuclide migration from repository sites because it may significantly lower the arrival times in the biosphere”

*Bodin, J., Delay, F., & de Marsily, G. (2003). Solute transport in a single fracture with negligible matrix permeability: 1. fundamental mechanisms. *Hydrogeology Journal*, *11*(4), 418–433. https://doi.org/10.1007/s10040-003-0268-2

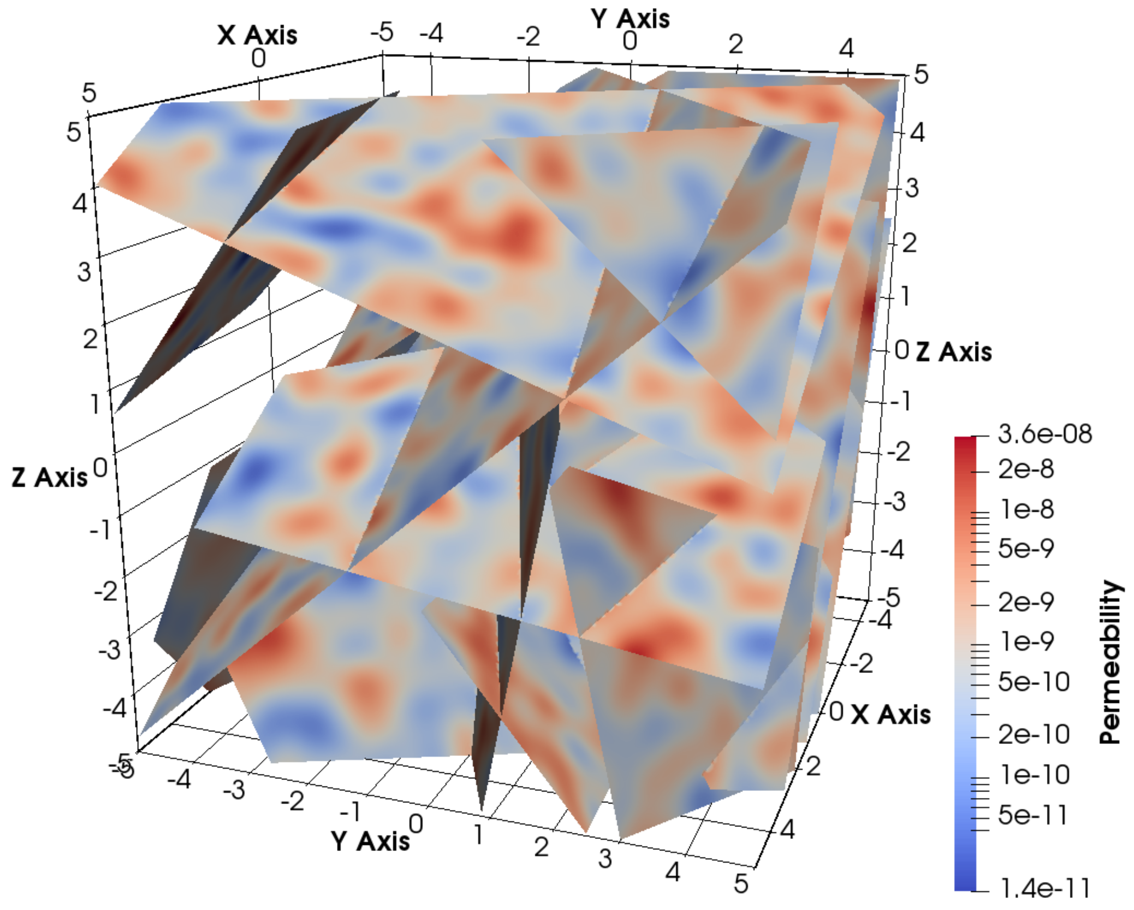
Background and motivation

- Hence, investigate the question:

What is impact of fracture roughness on flow and transport in DFNs?



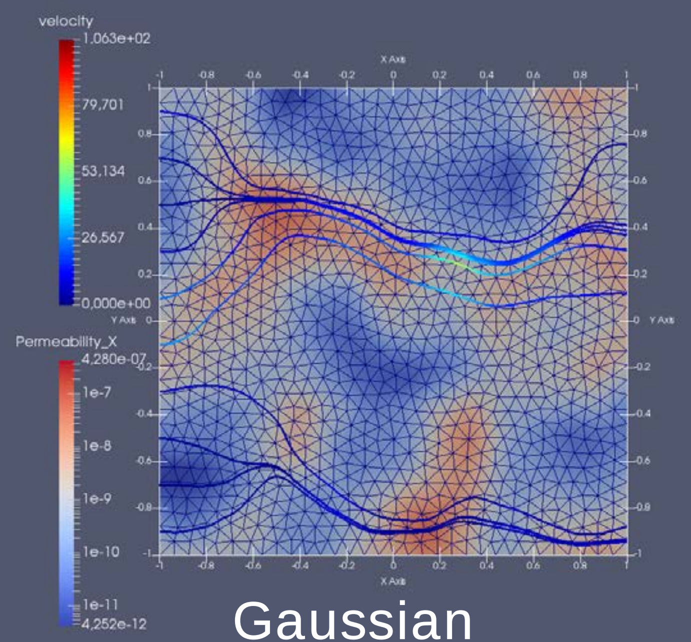
DFN with smooth fractures, no internal variability
Fractures assumed constant or effectively homogeneous



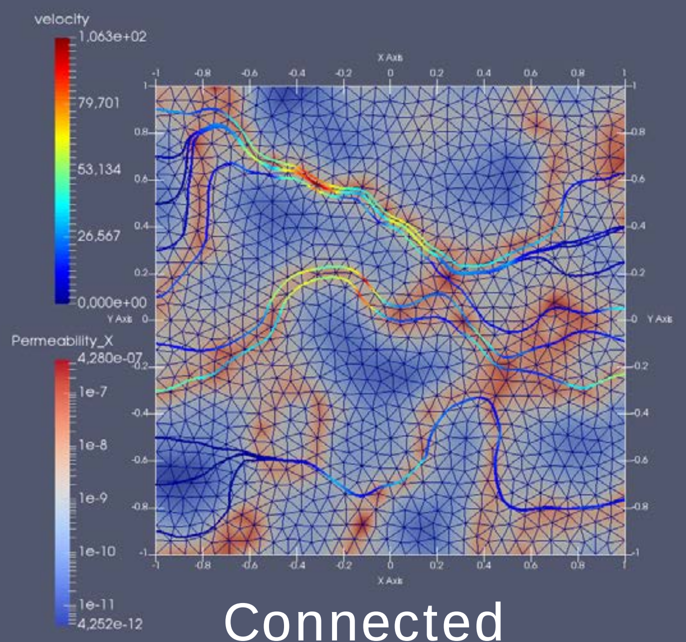
DFN with rough fractures,
Fractures are heterogeneous, have internal variability

Method to represent fracture roughness (internal fracture variability)

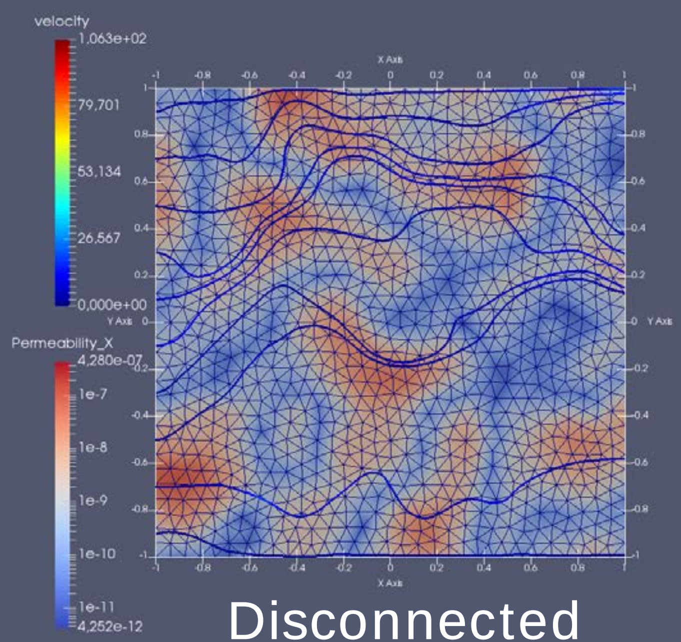
- Adopting Zinn and Harvey* (2003, WRR) approach for generating heterogeneity fields
- Yields triad of comparable textures: Gaussian, Connected, Disconnected
- Very different structural connectivity, but identical mean and variance
- Thus enables fair and consistent comparison between cases



Gaussian



Connected

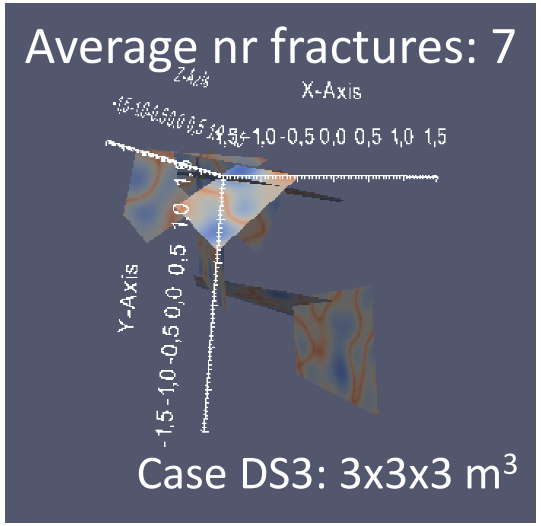


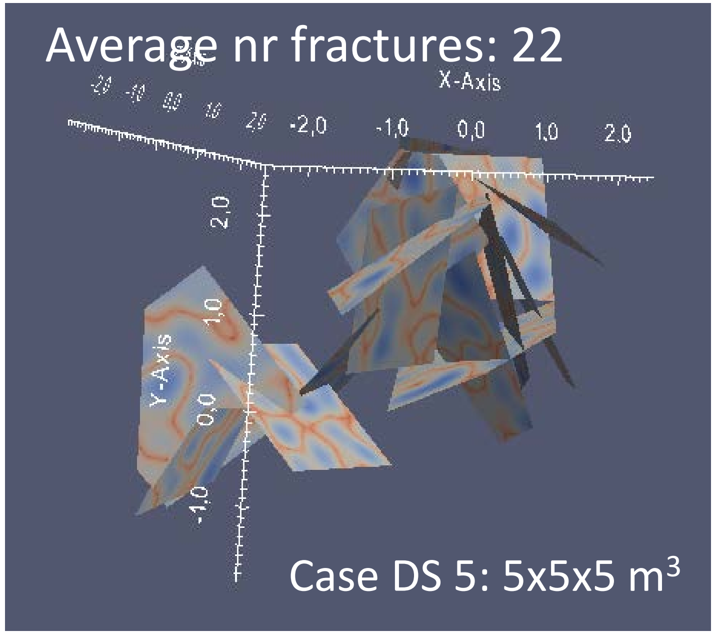
Disconnected

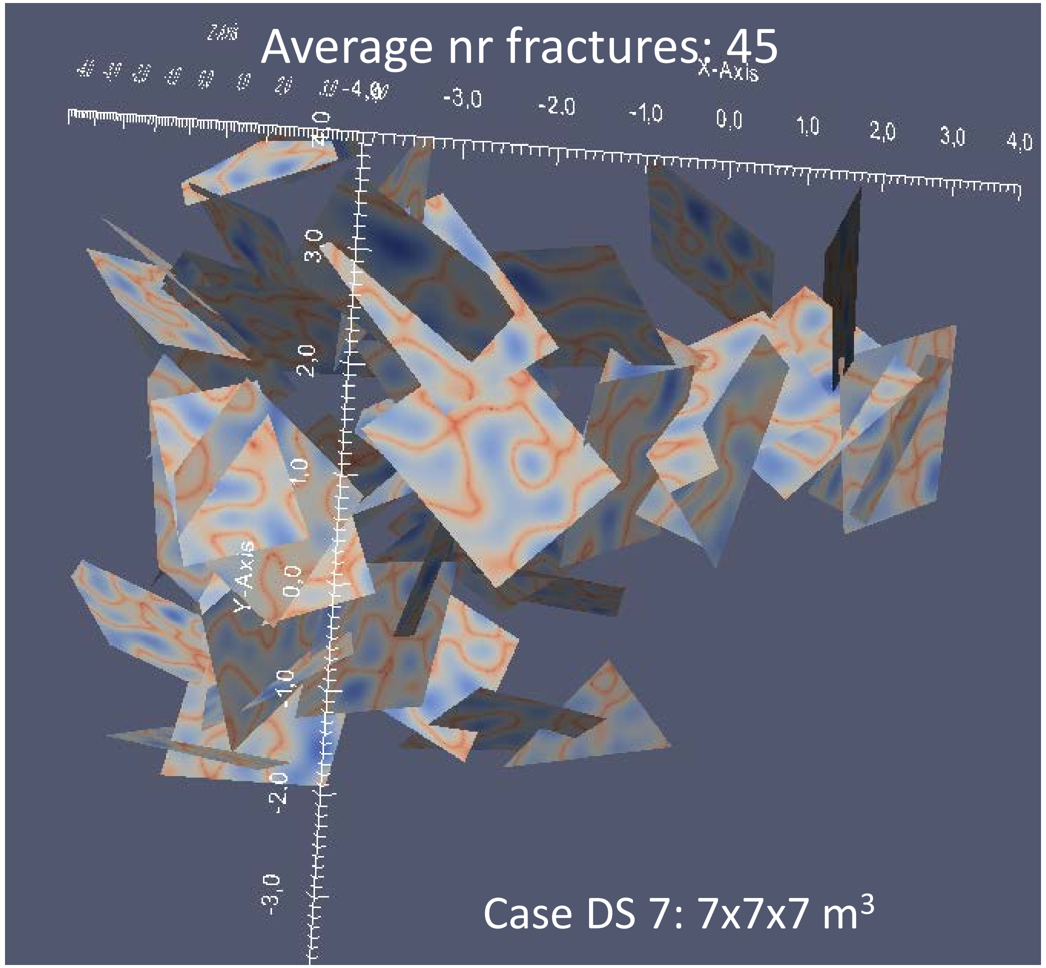
*Zinn, B., & Harvey, C. F. (2003). When good statistical models of aquifer heterogeneity go bad: A comparison of flow, dispersion, and mass transfer in connected and multivariate Gaussian hydraulic conductivity fields. Water Resources Research, 39(3). https://doi.org/10.1029/2001WR001146

Discrete fracture network sims, increasing nr fractures

- Systematic increase in domain size and hence number of fractures
- Considering Gaussian, Connected, Disconnected textures (Zinn & Harvey, 2003, WRR)
- Correlation lengths 2.5%, 7.5%, 12.5%, 25%
- Multiple realisations sampled for each case
- Model used is dfnWorks*





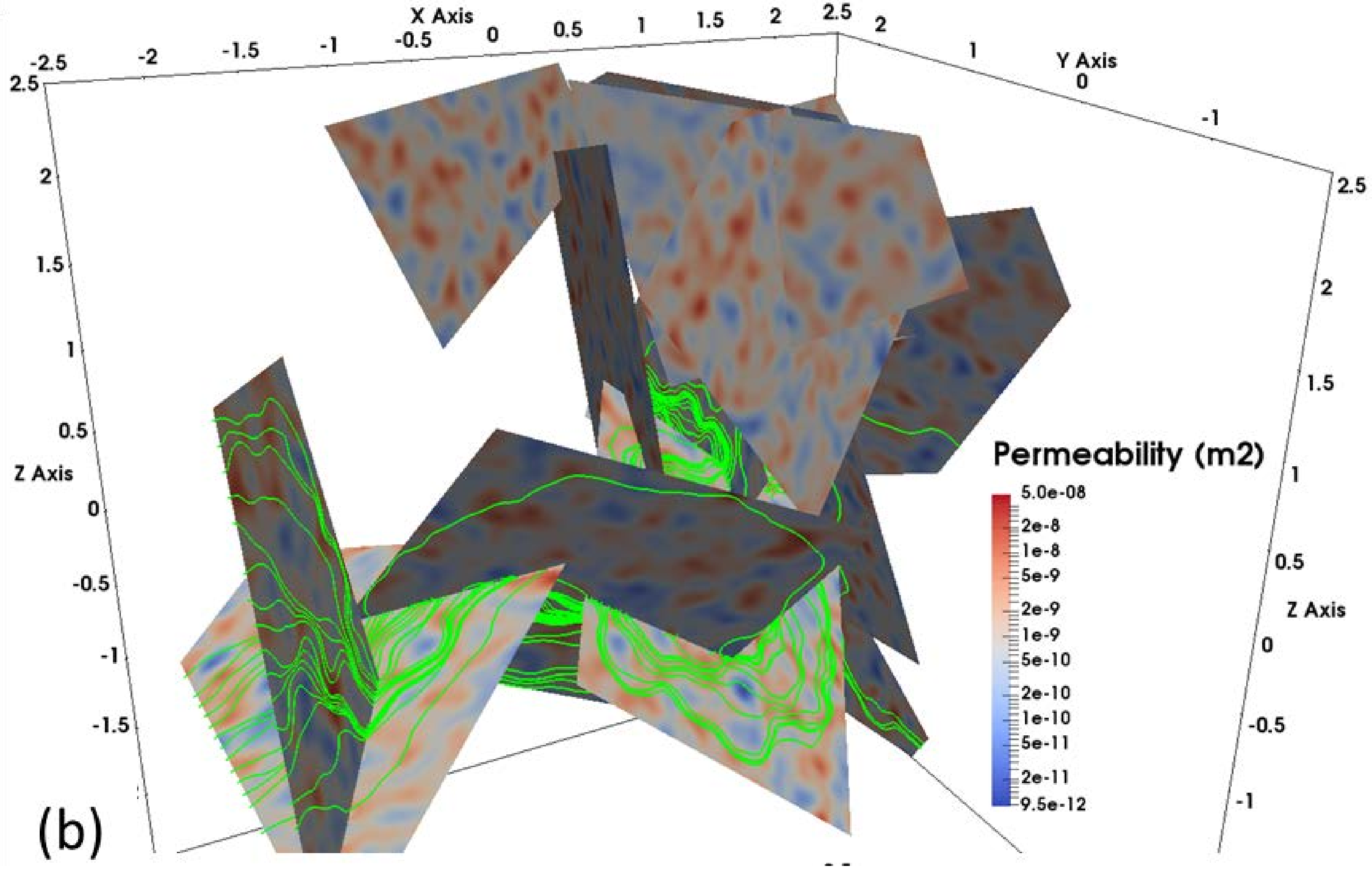


Frampton, A., Hyman, J. D., & Zou, L. (2019). Advective Transport in Discrete Fracture Networks With Connected and Disconnected Textures Representing Internal Aperture Variability. *Water Resources Research*, 2018WR024322. https://doi.org/10.1029/2018WR024322

**dfnWorks: Hyman, et al. (2015). dfnWorks: A discrete fracture network framework for modeling subsurface flow and transport. Computers & Geosciences, 84, 10–19. https://doi.org/10.1016/j.cageo.2015.08.001*

Trajectories, example realisation

- DFN domain DS 5: 5x5x5 m^3
- Average 22 fractures
- Gaussian heterogeneity case
- Correlation length λ=0.25 m
- Here showing one DFN realization, each realization samples ~1000 particles
- Here only 20 pathlines shown (green)
- Flow from –x to +x
- Injection: x = -2.5 m plane
- Arrivals: x = +2.5 m plane



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Early mass arrival

- Showing travel times of first 5% of CDF, normalised wrt smooth fracture case
- Horizontal axis shows cases of increasing domain size and hence increasing nr of fractures (DS 1, 2, 3, 5, 7; eg DS 7 is domain of size 7x7x7 m^3)
- Correlation lengths:

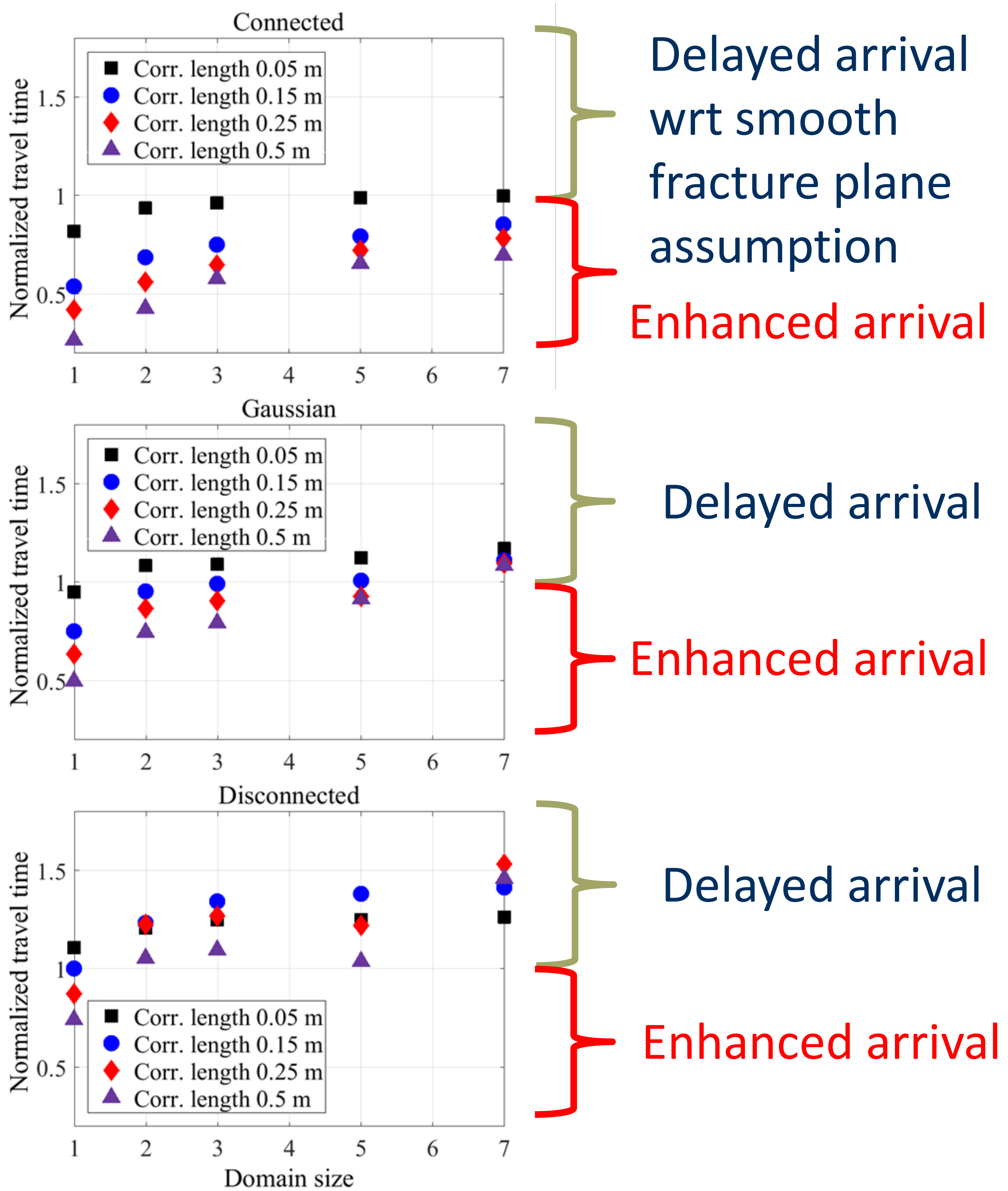
  0.05 m ~ 2.5% of fracture

  0.15 m ~ 7.5% of fracture

  0.25 m ~ 12.5% of fracture

  0.5 m ~ 25% of fracture

- → Enhanced arrival time for cases with greater roughness (correlation length), or cases with greater structural connectivity (Connected case, Gaussian case)
- → Still apparent even for larger DFNs for Connected case



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Intersections

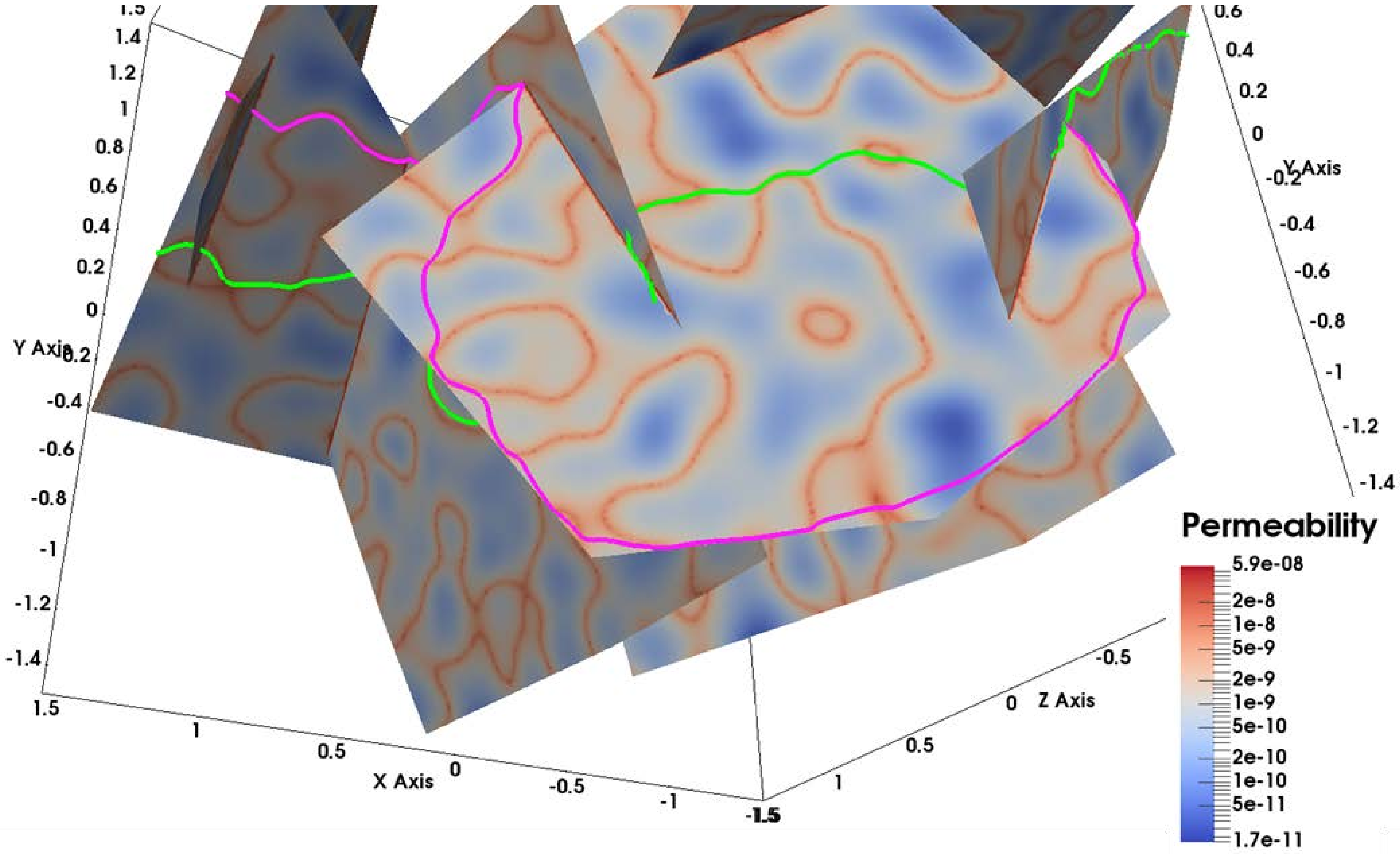
Fracture-fracture intersections act as chokes

What happens to pathways if intersections do not act as chokes?

Intersections are assigned high permeability to represent continuity in permeability across fracture-fracture intersections

Then, mean travel time decreased from 1.2 to 0.8 (normalised wrt smooth fracture case)

→ **Enhances transport**



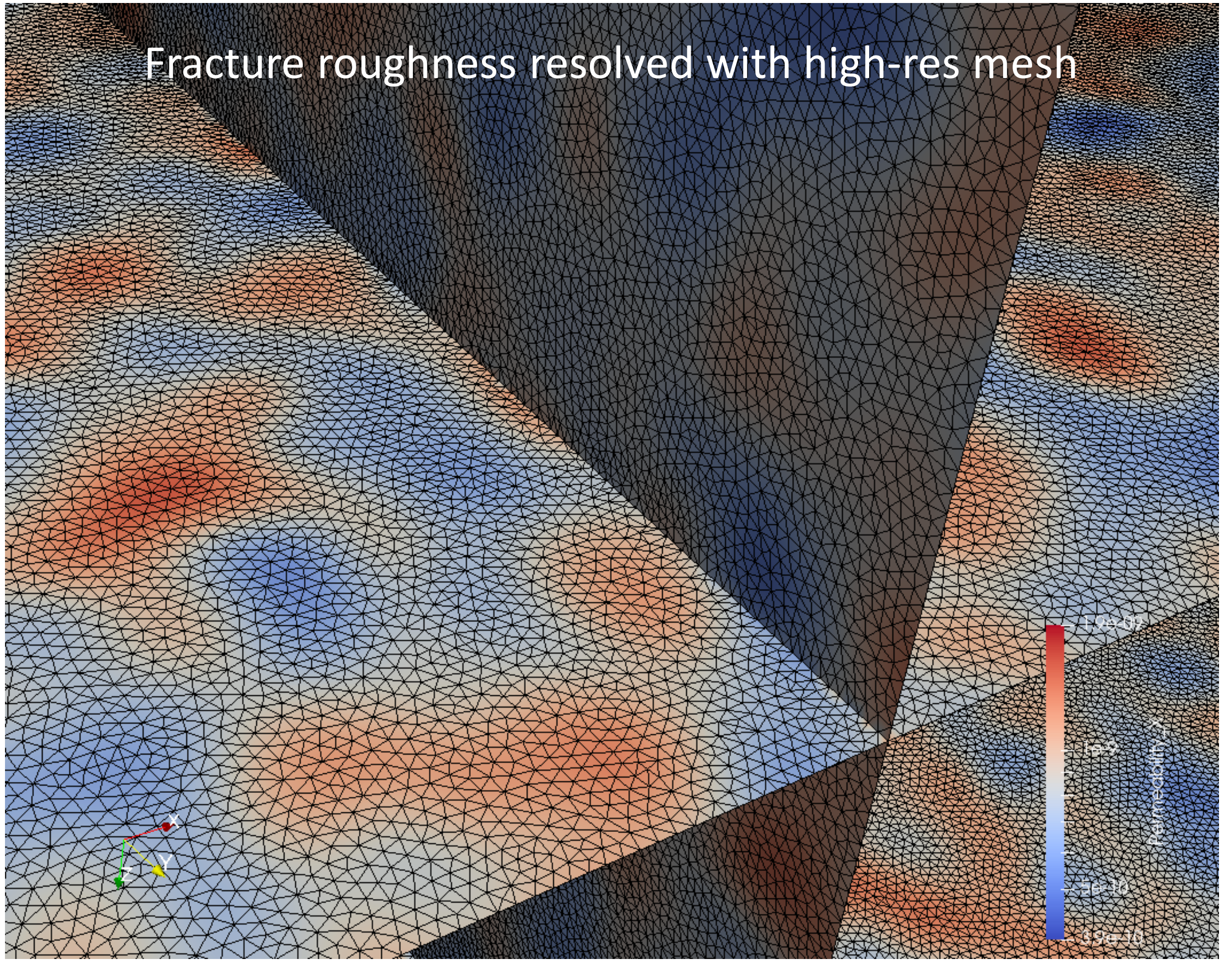
Intersections not modified, they act as chokes, yields $\tau = 1.2$ (e.g. purple)

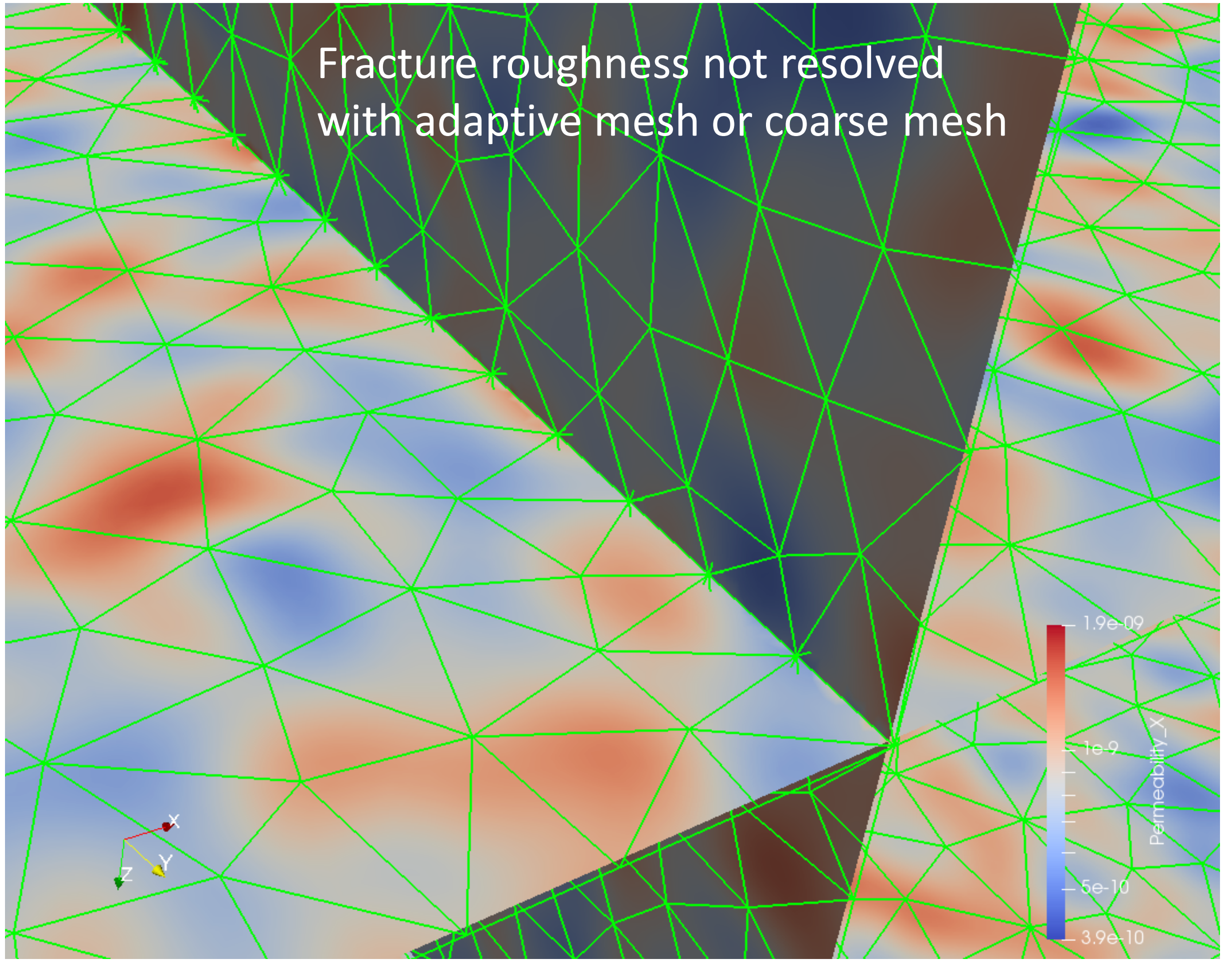
Intersections modified, they do not act as chokes, yields $\tau = 0.8$ (e.g. green)

Frampton, A., Hyman, J. D., & Zou, L. (2019). Advective Transport in Discrete Fracture Networks With Connected and Disconnected Textures Representing Internal Aperture Variability. *Water Resources Research*, 2018WR024322. https://doi.org/10.1029/2018WR024322

Numerical mesh of DFN model with fracture roughness

- Accounting for fracture roughness requires high-resolution mesh, not possible to employ adaptive meshing techniques
- Becomes increasingly computationally demanding for larger DFNs





Conclusions

- Smooth fracture plane assumption may lead to non-conservative estimates of transport in discrete fracture networks
- Transport enhanced (faster first arrivals) when accounting for fracture roughness, especially for cases with large variability and strong correlation structures
- Effect may diminish with increasing domain size (nr fractures)
- Accounting for roughness (internal fracture variability) may be critical for subsurface storage applications when conservative estimates are needed and to ensure robust safety analysis

- However, introduces challenges for numerical modelling because high-resolution mesh required
- Becomes increasingly computationally demanding for cases with significant internal variability and large number of fractures
- Further amplified when uncertainty analysis requires multiple Monte Carlo realisations

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