Estimating rockmass properties based on DFN methods

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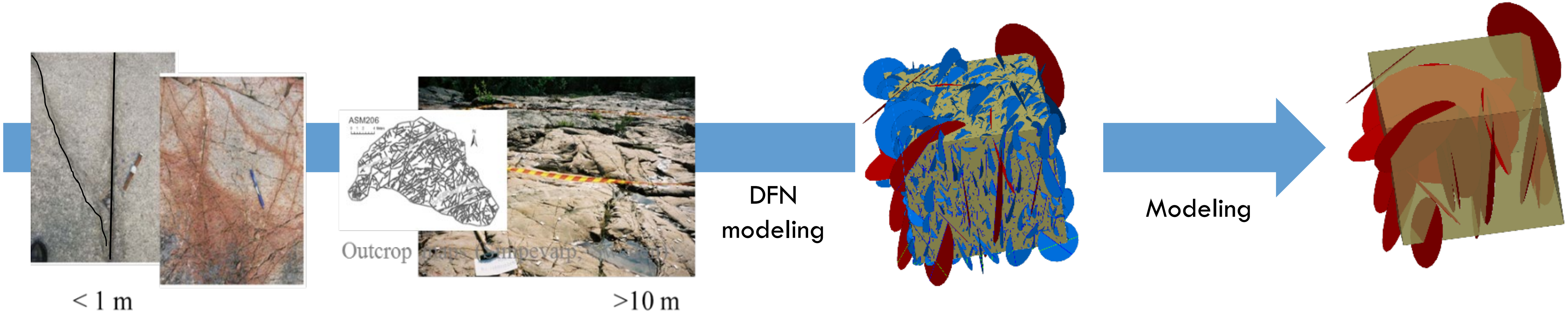
Objective: Introduce Discrete Fracture Network methods for rockmass modelling



Relevant complexity

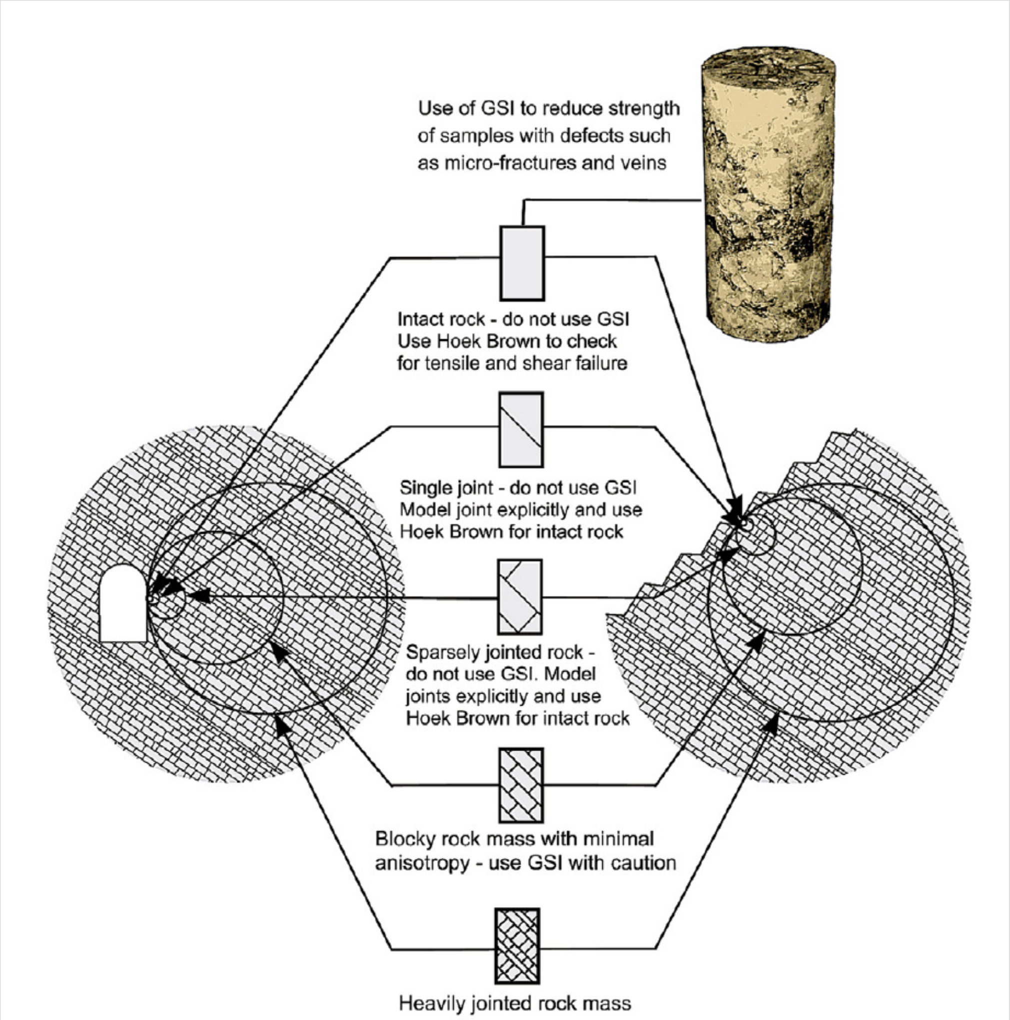
- Anisotropy
- Scale effect
- Integration from cm to km

Modeling purpose

- **Stress, strain,** hydraulic, transport, HM, thermal
- Available data
- Modeling as DEM, discrete or equivalent continuous modeling

Define which metric of a DFN is the controlling factor of rockmass elastic properties

Classical approach: fractured rock as a block assembly

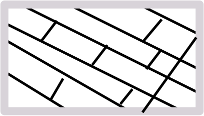


(Hoek and Brown, 2018)

(RQD, RMR, Q, GSI) are adapted to heavily jointed rock masses

- Assembly of blocks
- Several sets of potentially infinite fractures (isotropy)
- Fractured system Scale = **spacing**
- Applicable when **model resolution** >> **spacing**

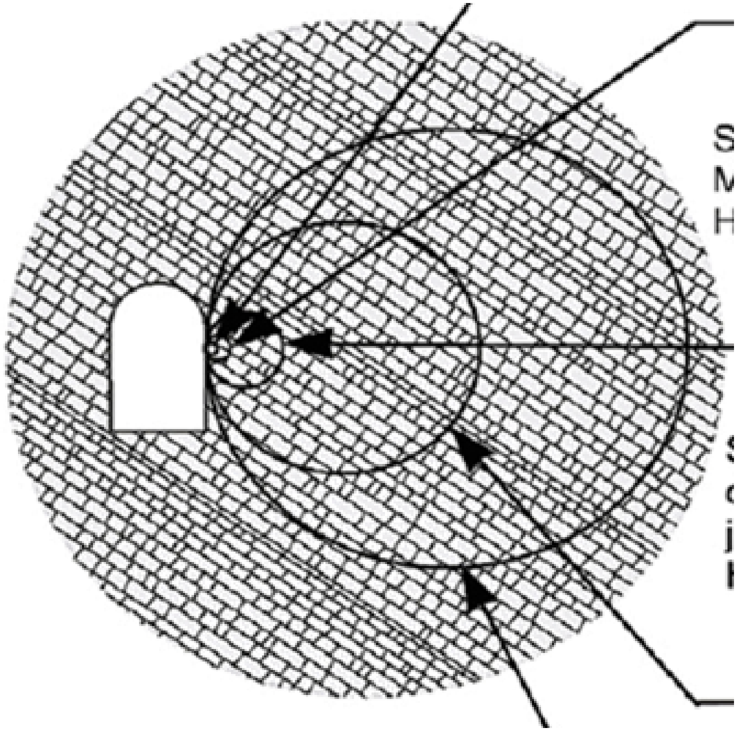
But lack of



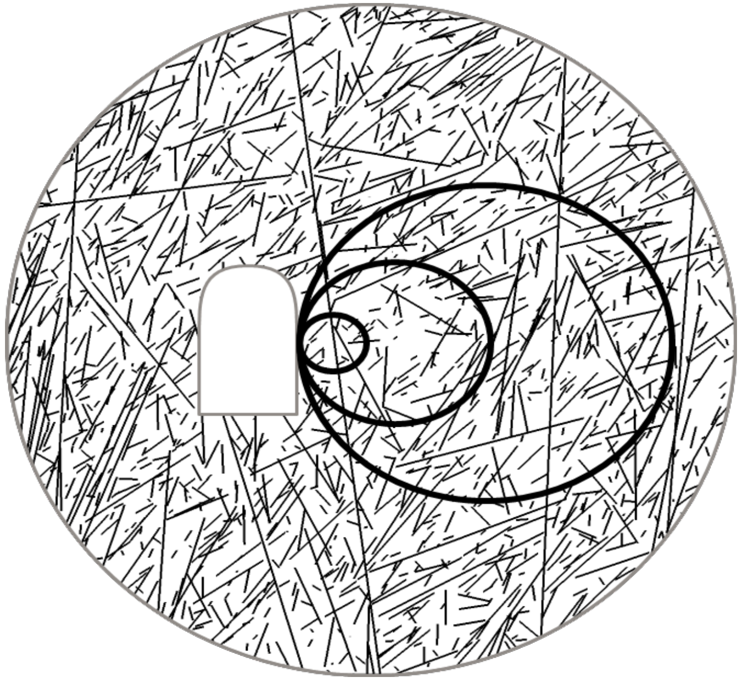
- Density and scale (size distribution of fractures)
- 3D representation
- Anisotropy
- Quantitative description

Concepts for fractured rock

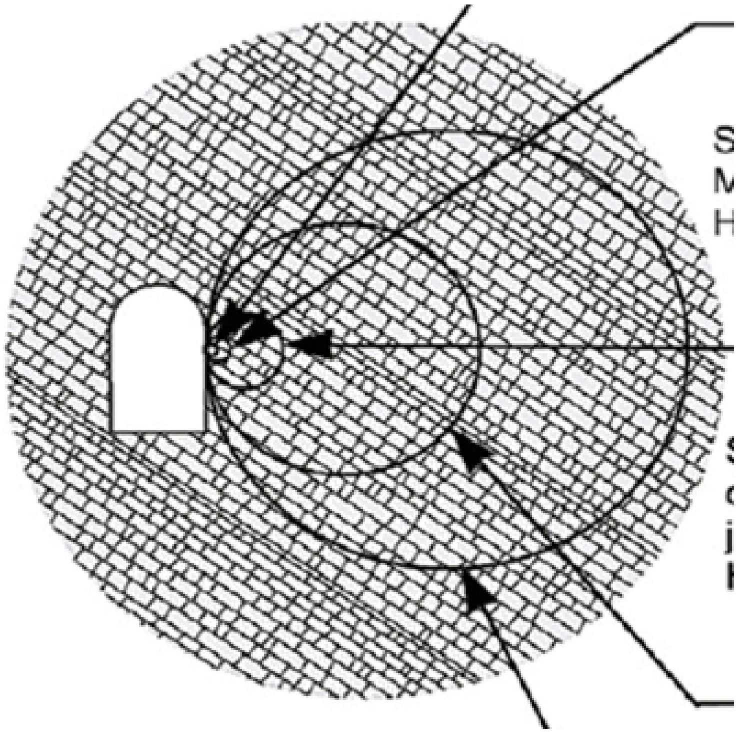
Block Assembly



population of individual fractures



Fractured rock – block Assembly vs Network of fracture



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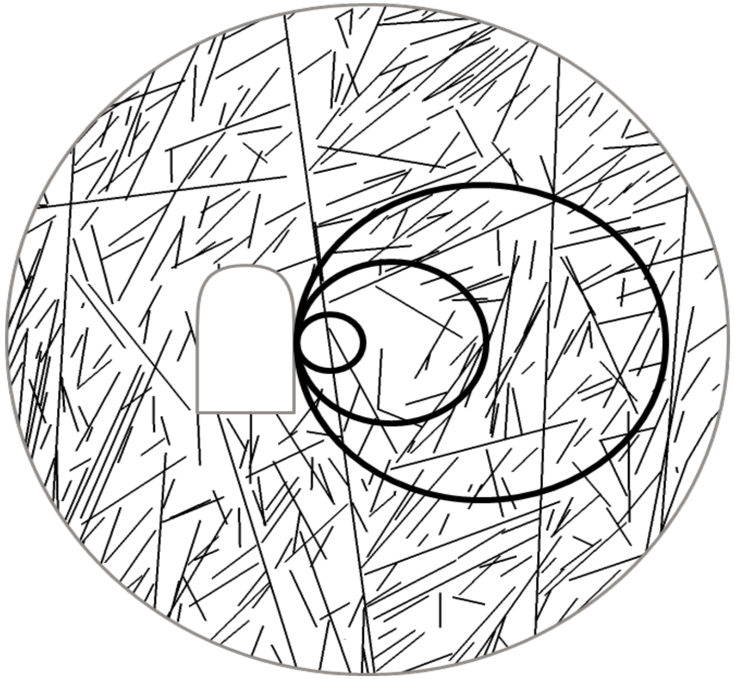

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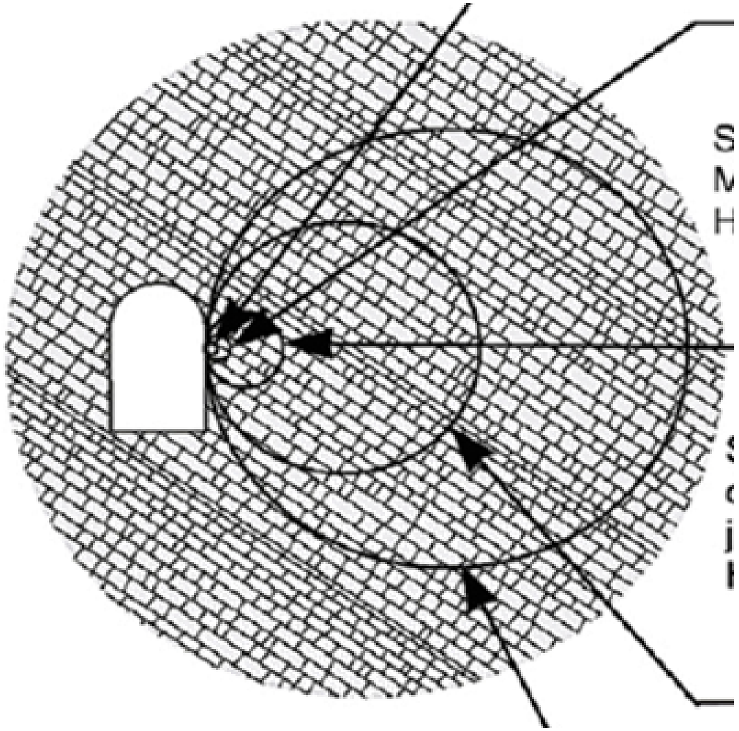
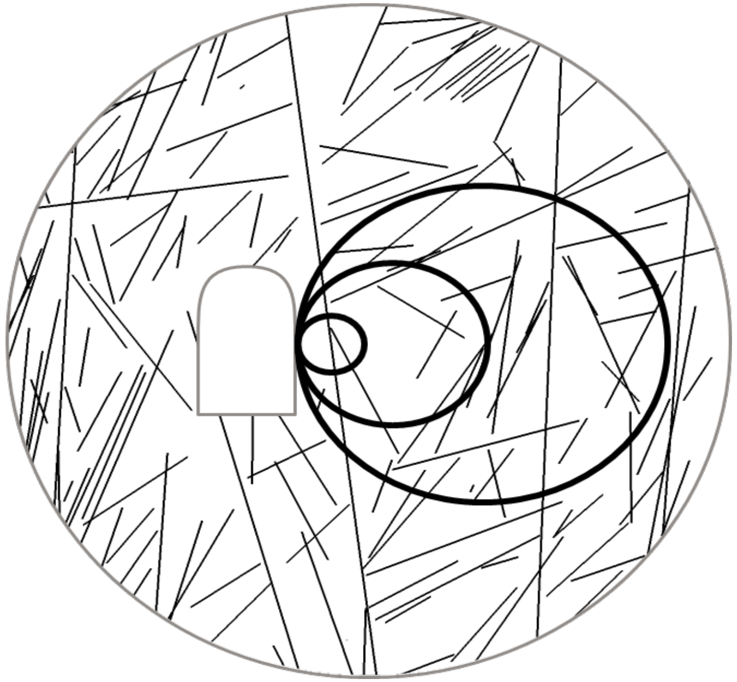
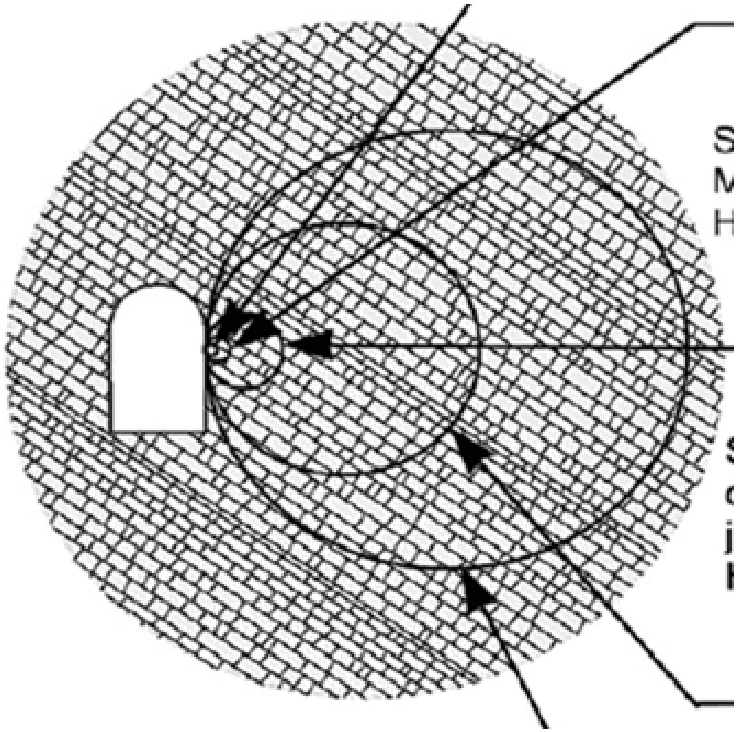


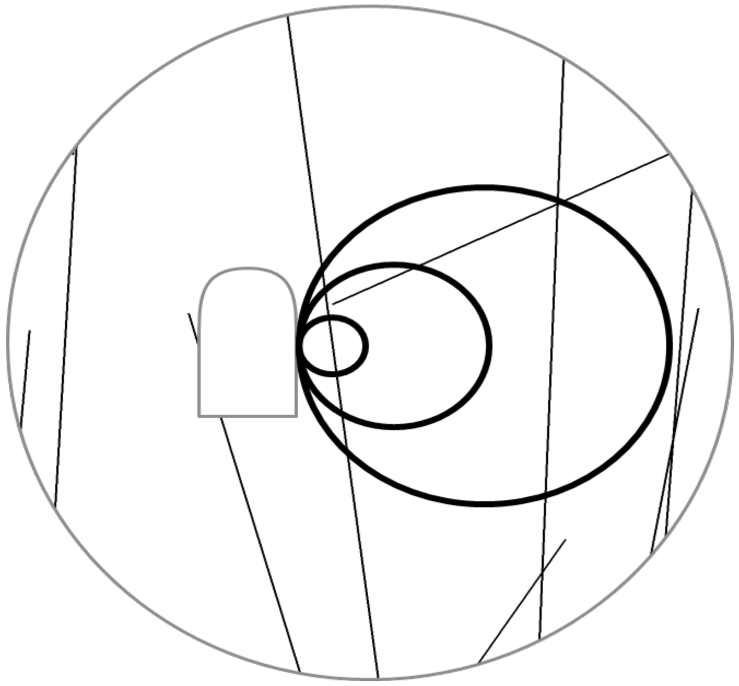
population of individual fractures



Fractured rock – block Assembly vs Network of fracture



population of individual fractures

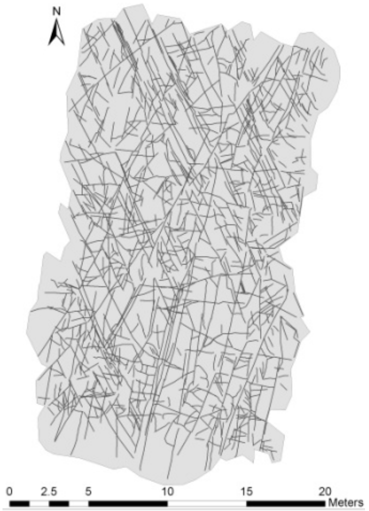


Need to assess the density vs size

Description of the fractured rock with DFN

Originally applied to

- Crystalline rocks
- Potential host for nuclear waste storage
- Connectivity, flow and transport modeling



Observation and mapping

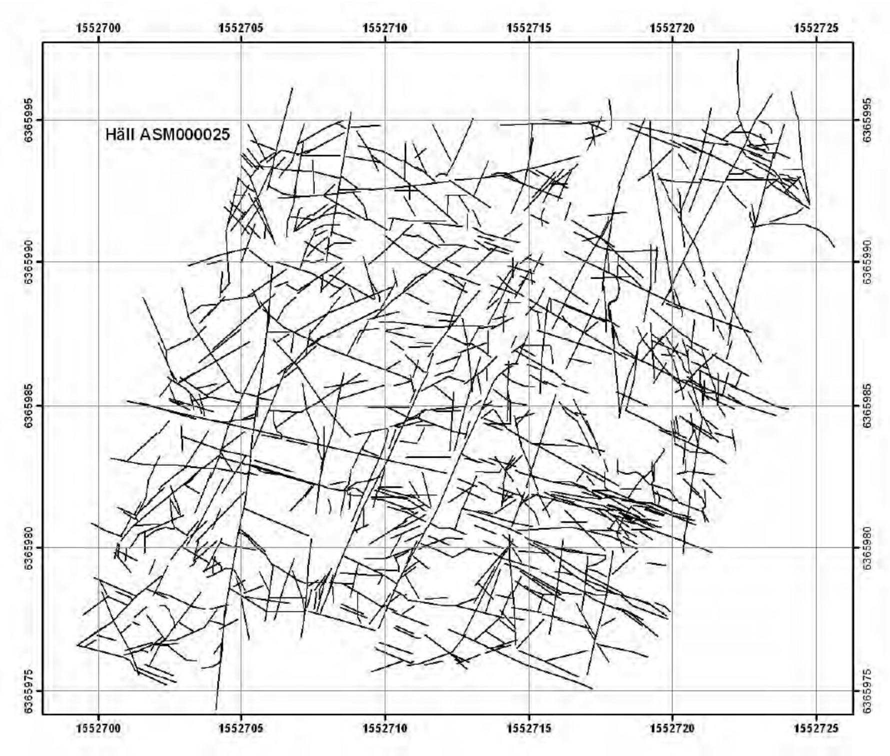
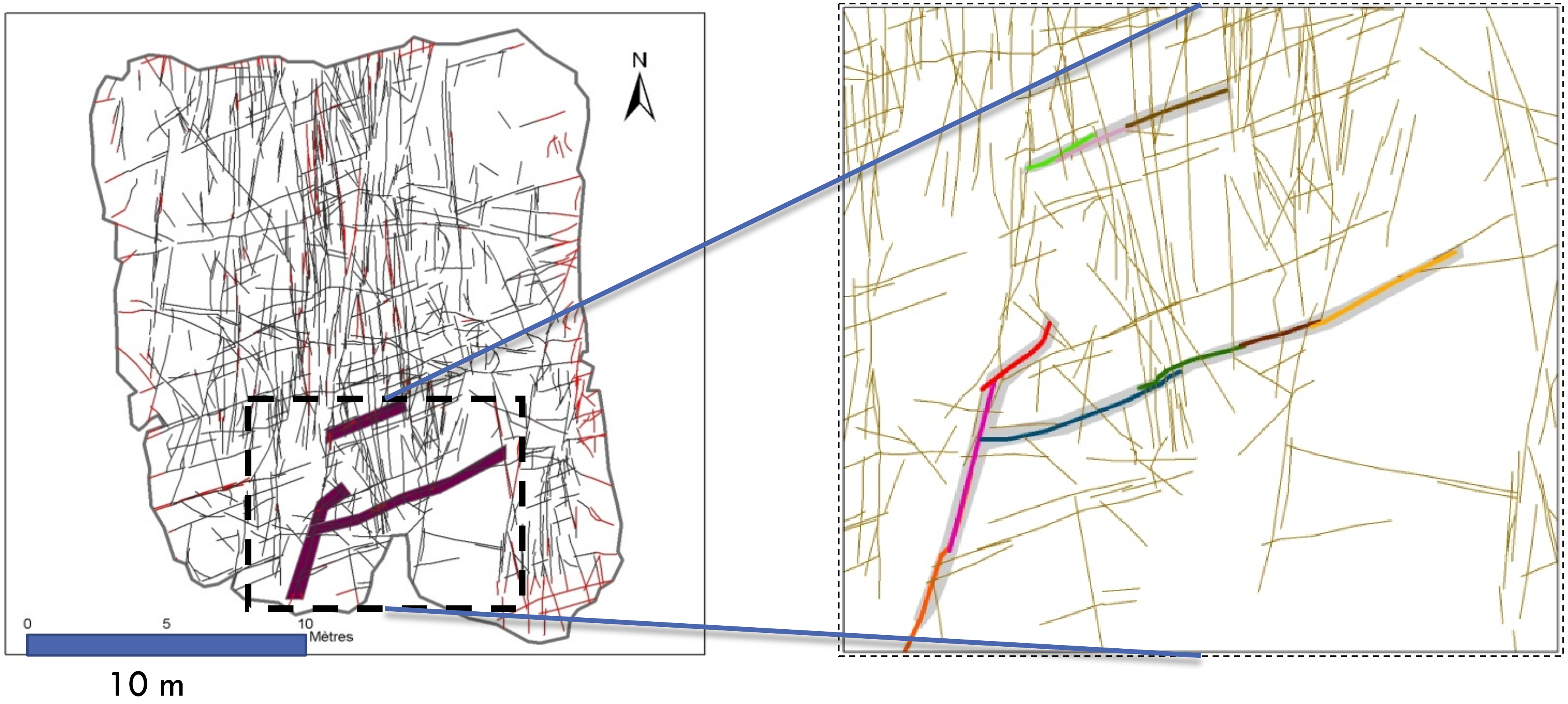


Figure 5-2. Fracture trace map of the ASM000025 outcrop.

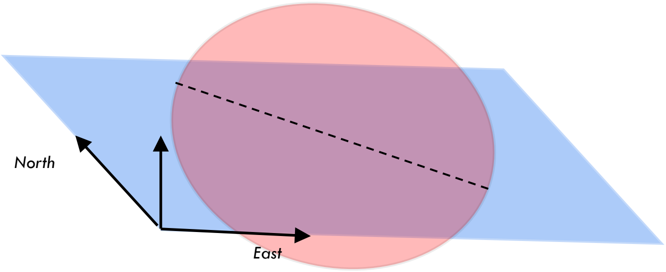
- Mapping conditions: Resolution and Censoring
- Physical boundaries of the distribution, *min* and *max* sizes, **not directly accessible**

A Fracture, what is it



A fracture in the model is an ensemble of fracture segments that define a consistent plane (mechanical coherence).

A Fracture, what is it



Roughly Planar discontinuity

Resulting from rock failure controlled by physical processes and field conditions

Can be cracks, joints, faults, shear zones, bedding planes

Lateral dimensions >> thickness

2D planar object

Position, size, orientation, shape

Flow, transport, mechanical properties

… to the fracture population (Discrete Fracture Network)

Build the **fracture size density distribution** $n(l)$

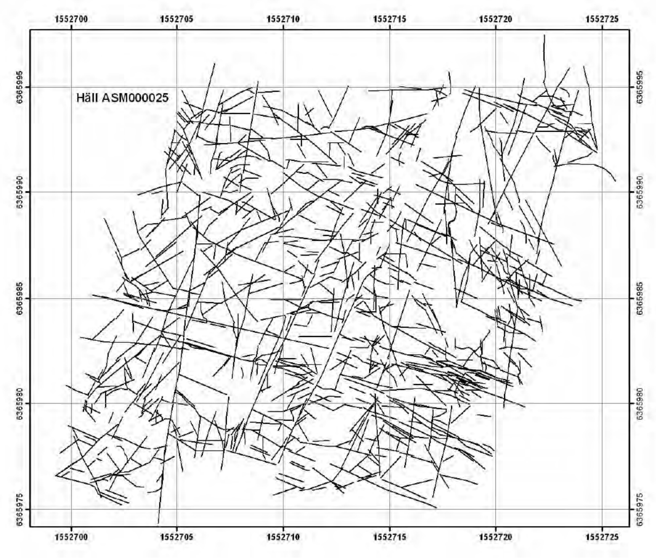


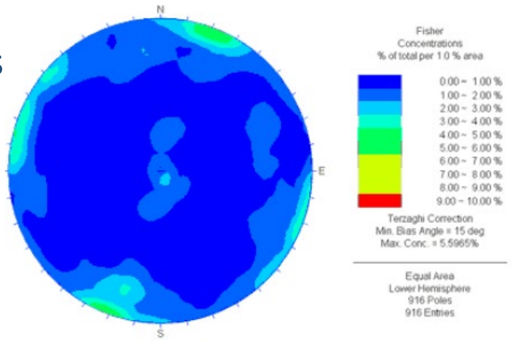
Figure 5-2. Fracture trace map of the ASM000025 outcrop.

[SKB report P-04-35]

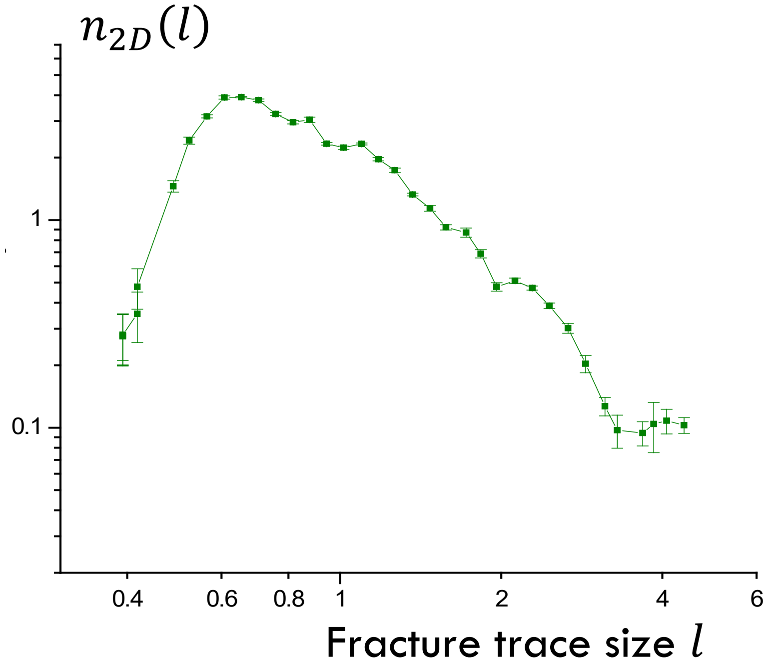
- Logarithmic binning to **count** the number of fracture traces whose size l' is in the range $l; l + dl$
- Normalized by map area and bin size

$$n_{2D}(l) = \frac{1}{area} \frac{N(l<l'<l+dl,L)}{dl}$$

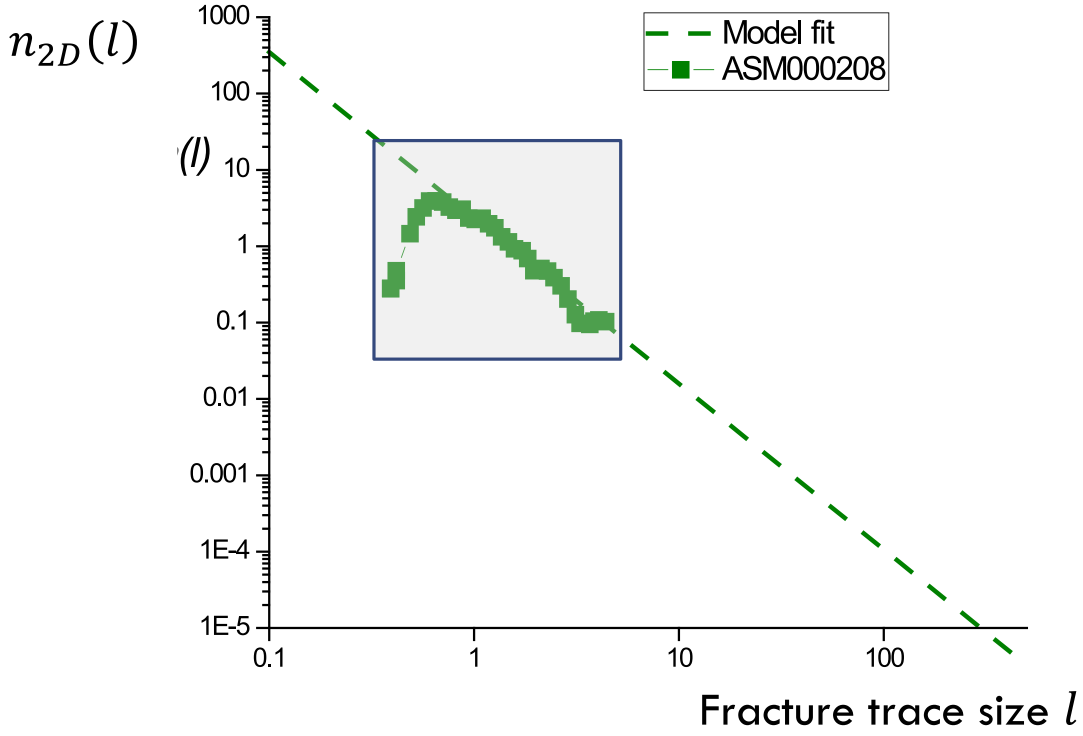
- Physical boundaries of the distribution, *min* and *max* sizes, **not directly accessible**
- Count orientations
- Variability …



- Stereological analysis required for a 3D model



Example – 2D trace size distribution

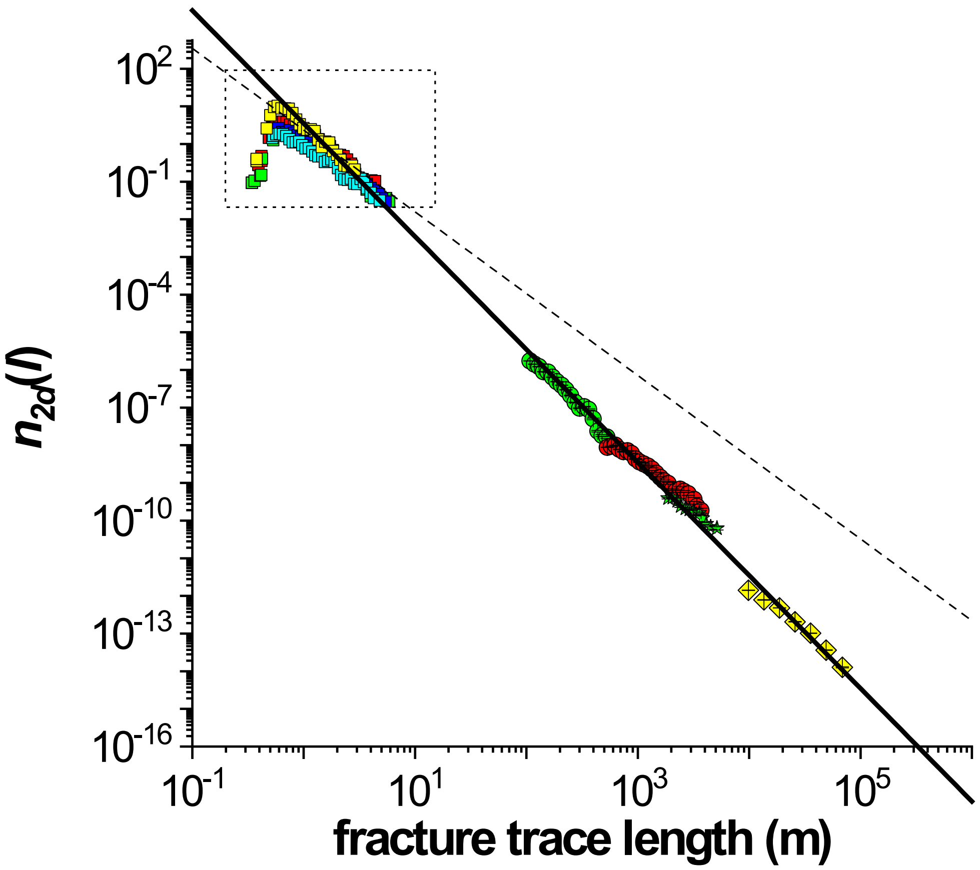


- Power-law trend may be identified

  $$n(l) = \alpha \cdot l^{-a}$$

- from a limited observation range
- parameters independent from observation range

From data to size distributions – Laxemar site

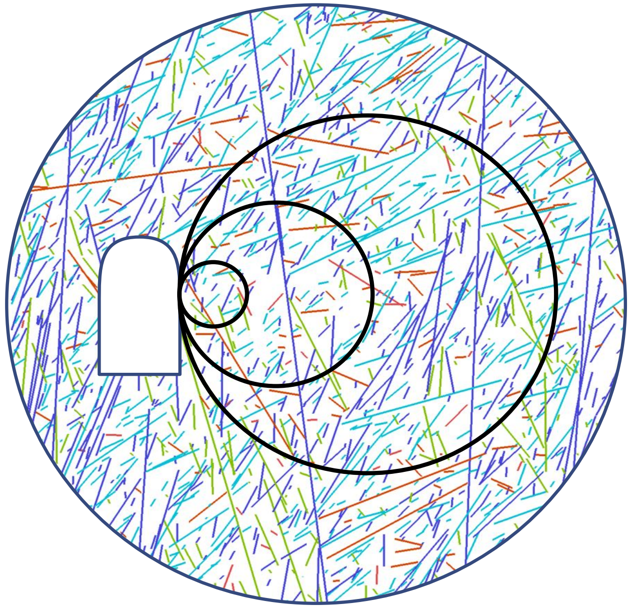


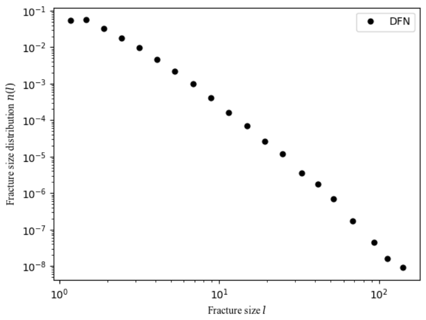
Power-law model for $n(l)$ consistent with observations

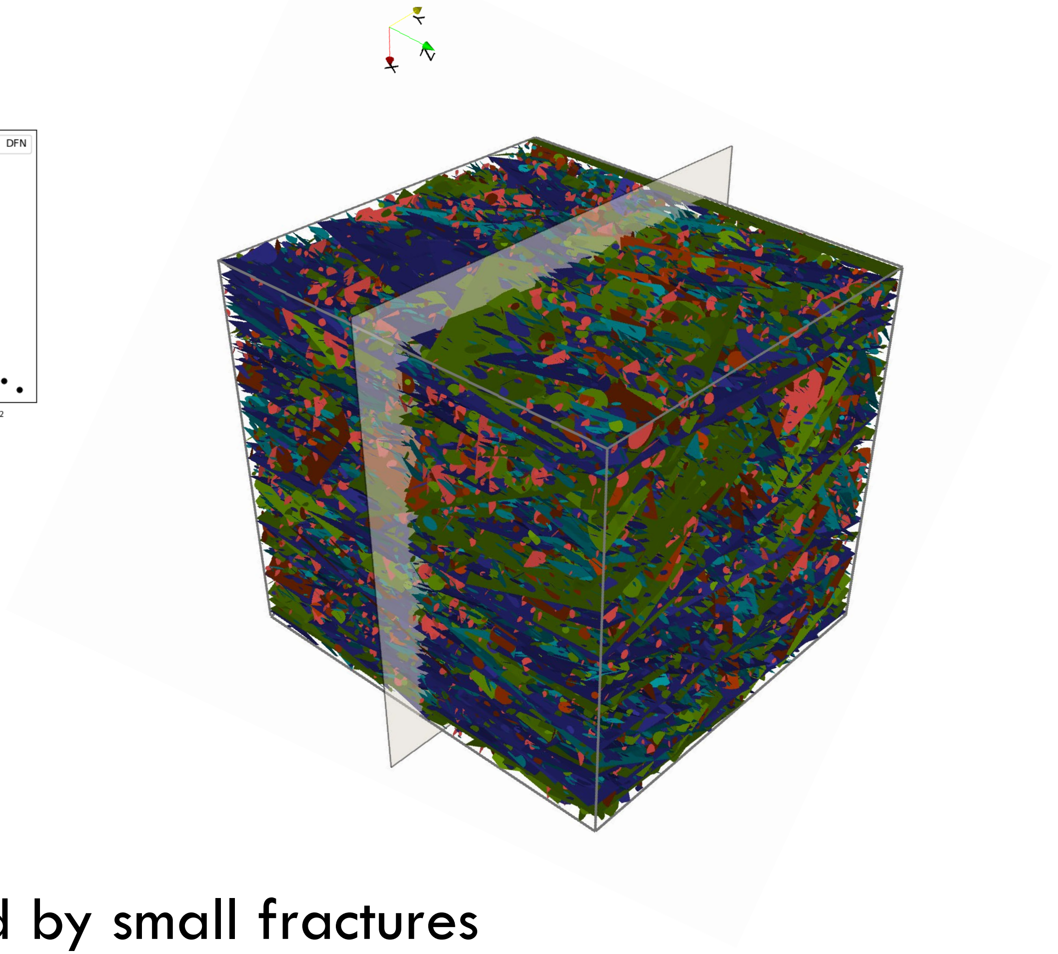
Single or double power-law model

Power-law model is a good proxy to model density variation with scale

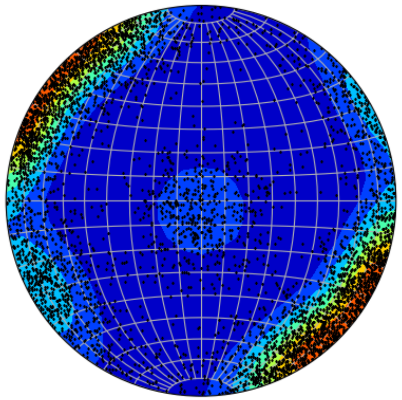
DFN in the Rockmass





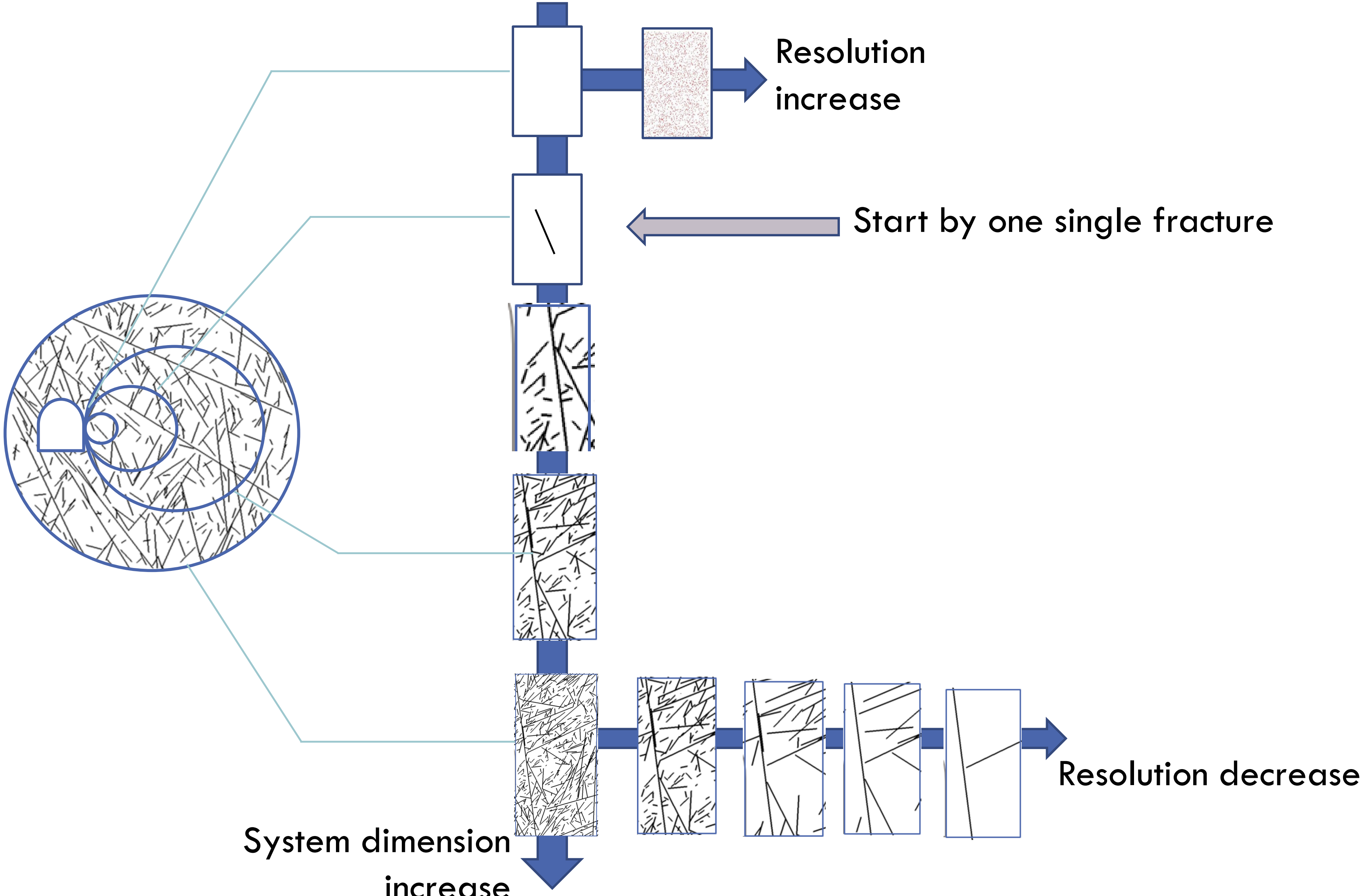


- Multiscale DFN
- No a priori REV



- P_{32} (m^2/m^3) dominated by small fractures
- Connectivity related to large fractures
- Mechanical properties potentially related to size and orientations

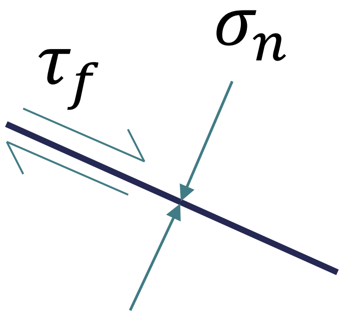
Scale, resolution, size, density

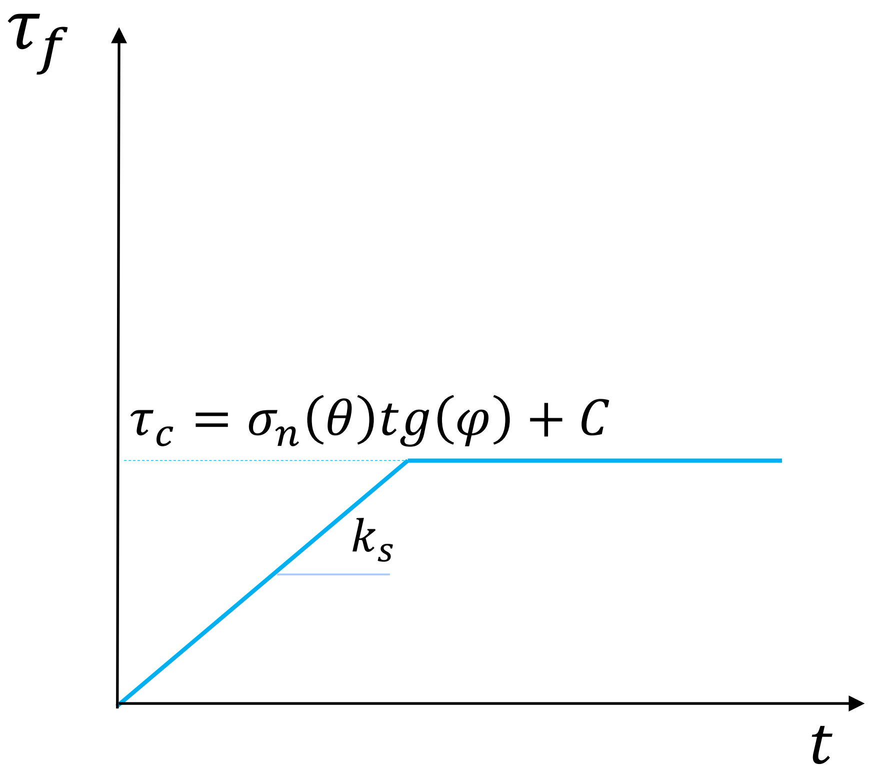


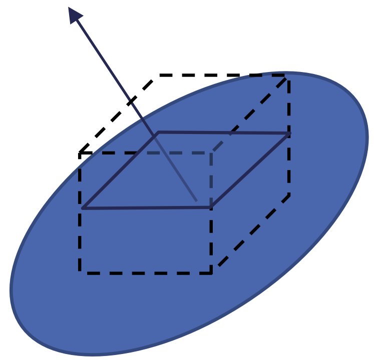
Predicting equivalent elastic properties

- From single fracture to fracture population (DFN)
- DFN: any set of disc-shaped planar fractures (multi-oriented, multi-scale)
- Elastic conditions (no damage)
- Rock matrix: isotropic elastic, Young's modulus E_m and Poisson ratio ν_m
- Fracture mechanical model
  - Coulomb slip , cohesion (c), friction (angle φ), normal (k_n) and shear stiffness (k_s)

Mechanical model - single fracture







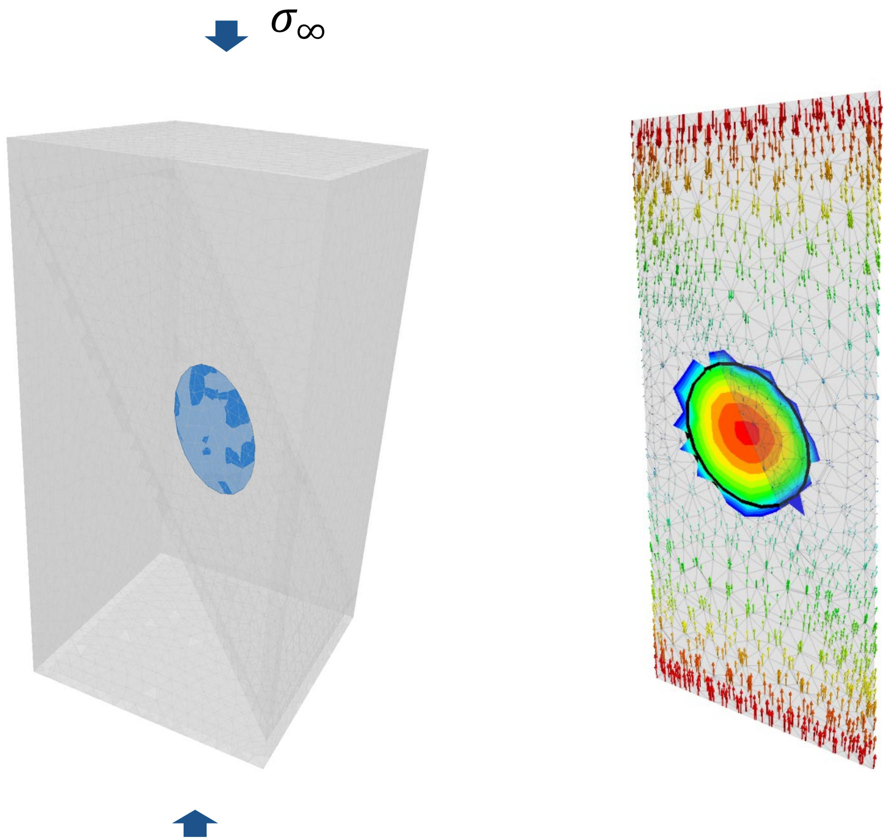
$\tau_f = k_s \cdot t$ if $\tau_f < \tau_c$

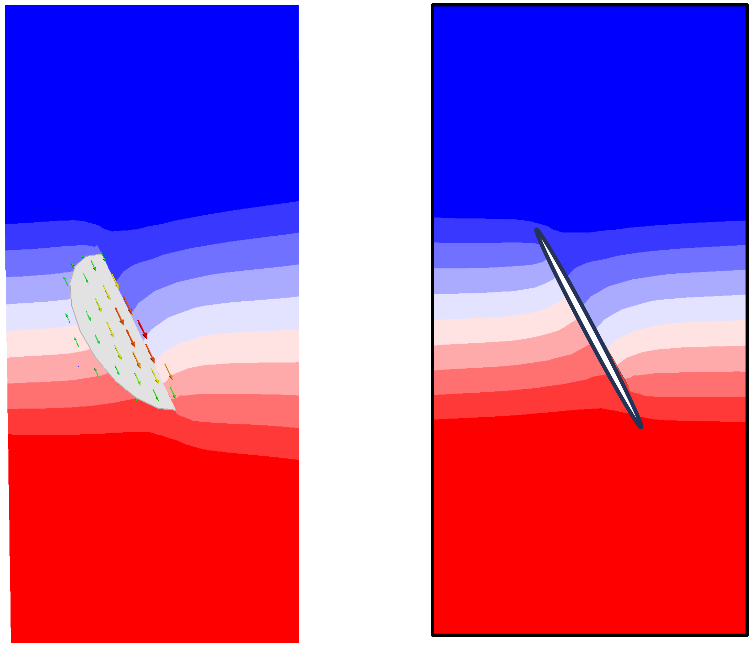
$\tau_f = \tau_c$ if $\tau > \tau_c$

$\tau_f = 0$ if $\varphi = 0$ or $k_s = 0$

Frictionless fracture

Single fracture isolated





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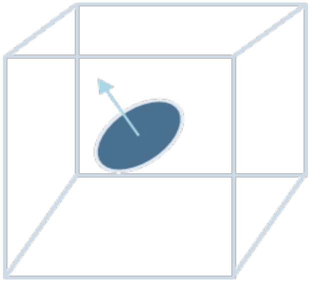
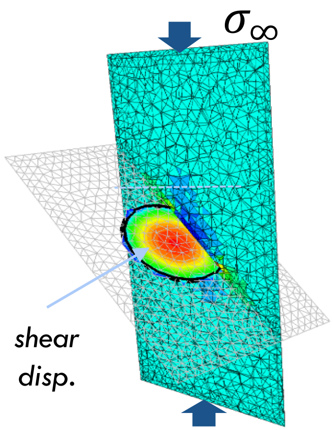
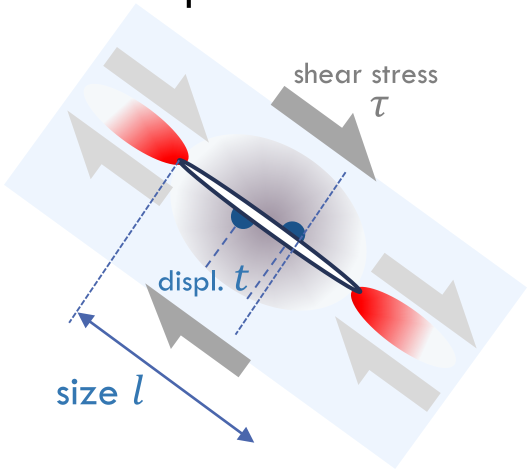
Frictionless isolated fracture

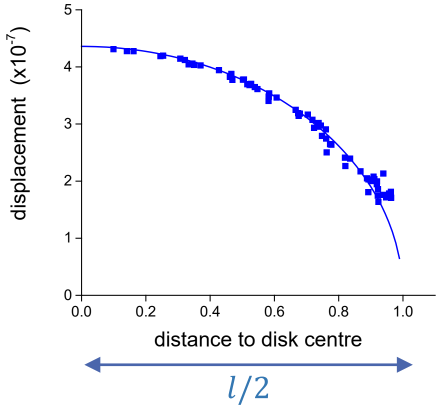




Stress and displacement at fracture



Displacement profile



Remote stress
τ shear stress
Intact rock
ν_m Poisson ratio
E_m Modulus

Fracture
l size
t average shear displacement

k_m equivalent matrix to fracture stiffness

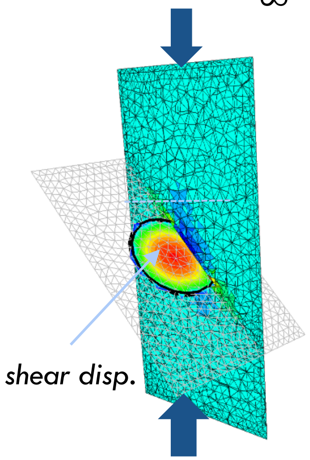
$$\boldsymbol{t} = \frac{\tau}{k_m}$$

$$\boldsymbol{k_m} = \frac{3\pi}{8} \cdot \frac{1-\nu_m/2}{1-\nu_m^2} \cdot \frac{E_m}{l} \sim \frac{E_m}{l}$$

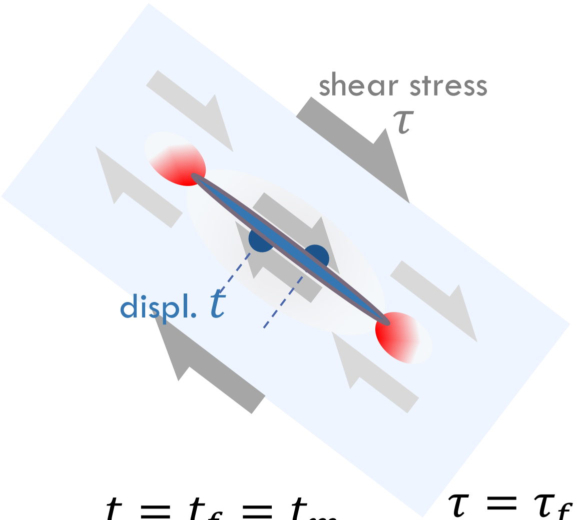
Frictional isolated fracture

Fracture friction, cohesion and stiffness terms

[Davy et al, 2018]



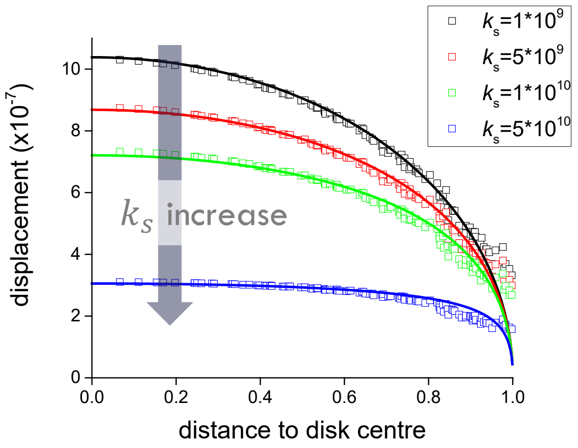
Stress and displacement at fracture

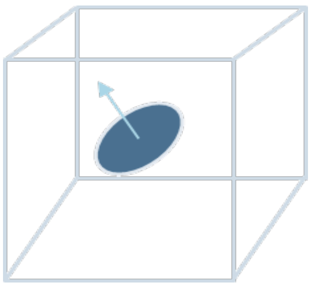


$$t = t_f = t_m \qquad \tau = \tau_f + \tau_m$$

$$\boldsymbol{t} = \frac{\tau}{k_m + k_s}$$

Displacement profile





Remote stress

τ shear stress

Intact rock

ν_m Poisson ratio

E_m Modulus

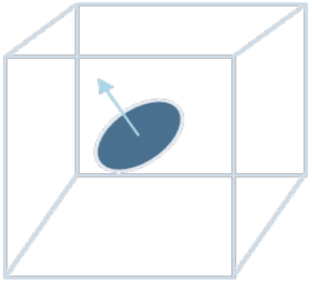
Fracture

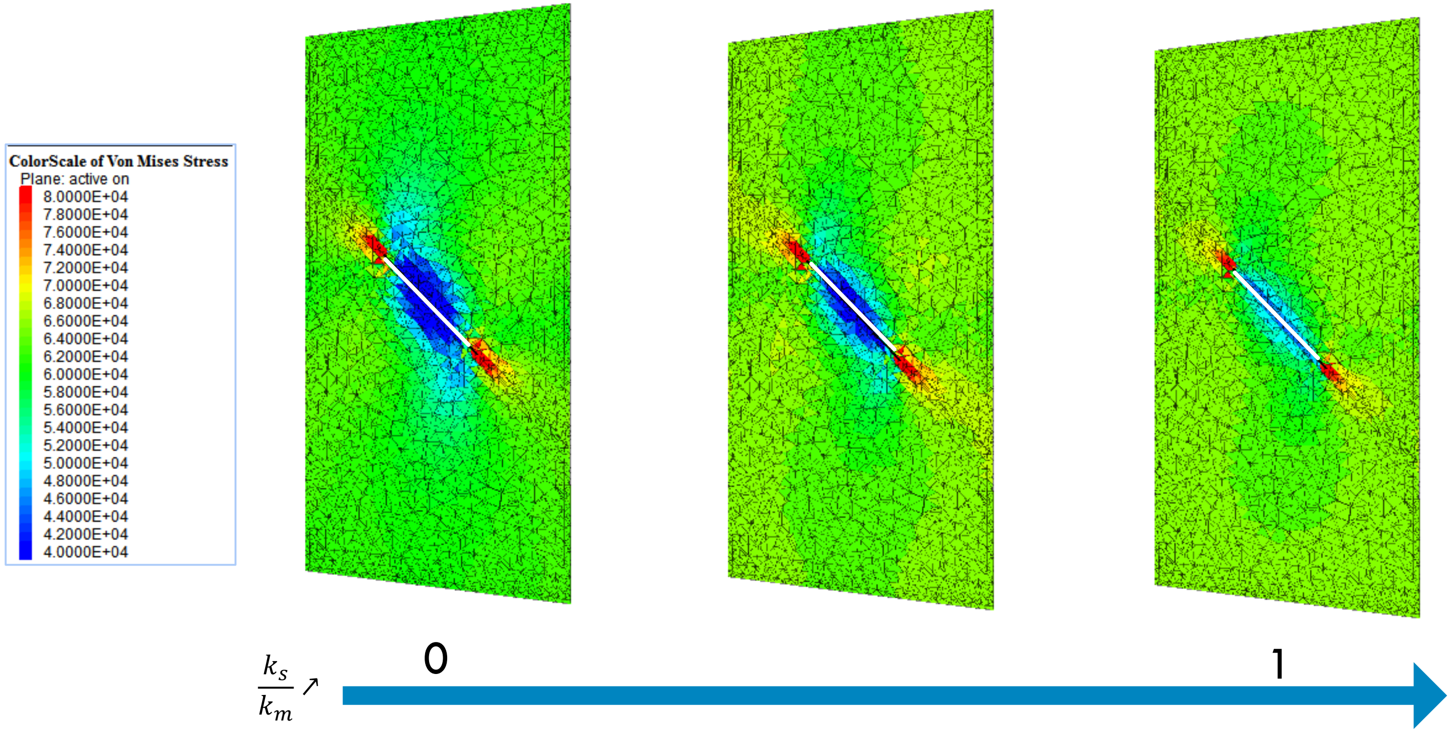
l size

t average shear displacement

$k_m \sim \frac{E_m}{l}$ equivalent matrix to fracture stiffness

Stress perturbation around a fracture





Increasing k_s relatively to k_m decreases the stress perturbation

Remote stress

τ shear stress

Intact rock

ν_m Poisson ratio

E_m Modulus

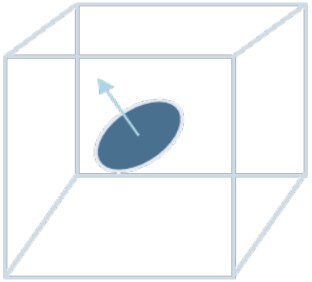
Fracture

l size

t average shear displacement

$k_m \sim \frac{E_m}{l}$ equivalent matrix to fracture stiffness

Two regimes for the shear displacement



with $l_s = \frac{E_m}{k_s}$

$l \ll l_s \Rightarrow t = \frac{\tau}{k_s + k_m} \approx \frac{\tau}{k_m} \propto l$

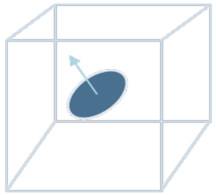
If k_s is negligible, fracture size defines the shear displacement

$l \gg l_s \Rightarrow t = \frac{\tau}{k_s + k_m} \approx \frac{\tau}{k_s}$

If k_s is dominant, shear displacement is independent from fracture size

→ Fracture sizes are critical

Shear vs slipping regime for $l \ll l_s$

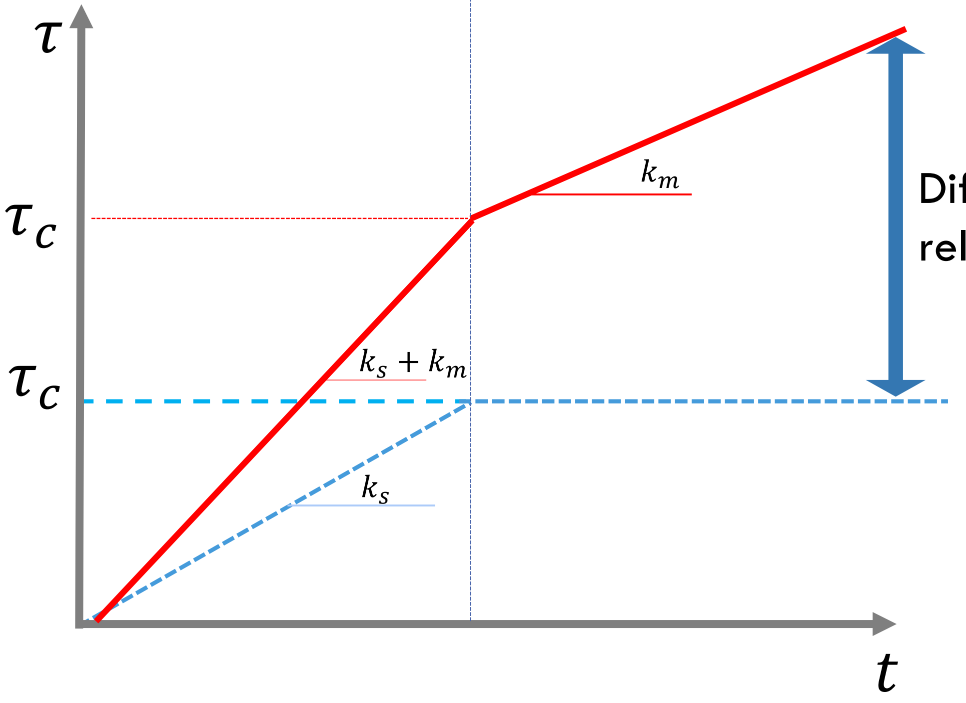


Shear regime

Slip regime

Critically stressed fractures

$$\tau_c^* = \frac{k_s + k_m}{k_s} \cdot \tau_c$$



Difference related to l/l_s

Critically stress regime threshold is size dependent

Remote stress

τ shear stress

Intact rock

ν_m Poisson ratio

E_m Modulus

Fracture

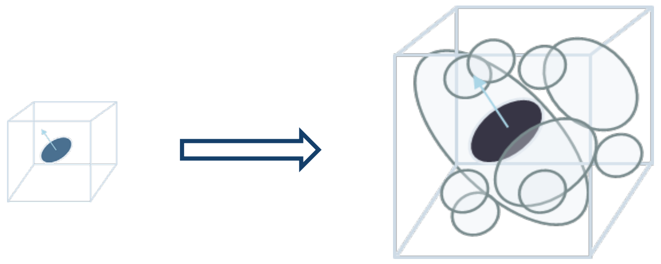
l size

t average shear displacement

$k_m \sim \frac{E_m}{l}$ equivalent matrix to fracture stiffness

Fracture sizes are critical

From single fracture to DFN and rock mass



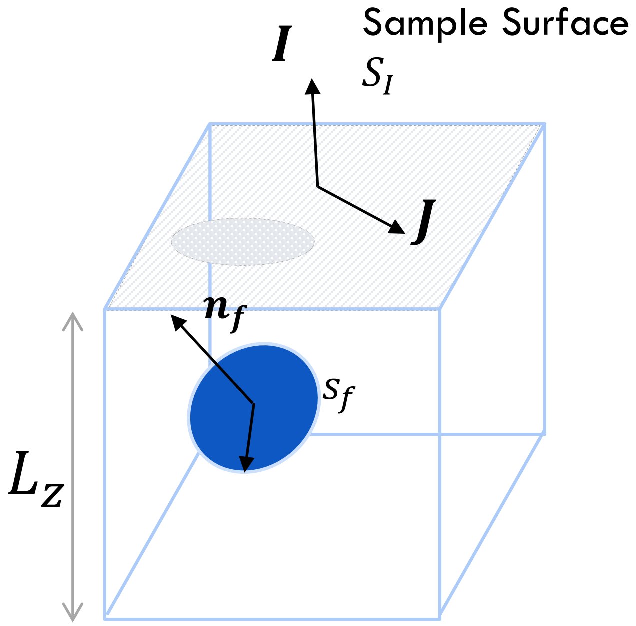
Rock mass with DFN

DFN contribution to rock mass strain tensor $\bar{\bar{\epsilon}}$:
Sum the contribution of each fracture f and intact rock m

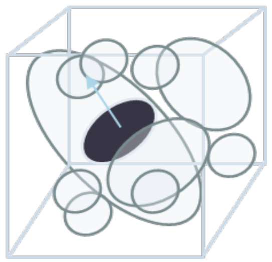
$$\epsilon_{ij} = \sum_f (\epsilon_{ij})_f + (\epsilon_{ij})_m$$

Fracture f contribution to rock mass strain

$$(\epsilon_{ij})_f = \frac{S_f(\mathbf{n_f}.\boldsymbol{I})}{S_I} \cdot \frac{t_f(\mathbf{s_t}.\boldsymbol{J})}{L_z} = \frac{S_f t_f}{V} \cdot (\mathbf{n}.\boldsymbol{I})(\mathbf{s}.\boldsymbol{J})$$



Fracture network to rock mass strain



DFN contribution to rock mass strain tensor $\bar{\bar{\epsilon}}$:
Sum the contribution of each fracture f and intact rock m

$$\epsilon_{ij} = \sum_f \left(\epsilon_{ij}\right)_f + (\epsilon_{ij})_m$$

Derive effective compliance tensor components C_{ijkl}:

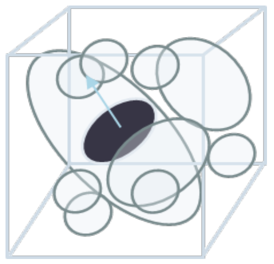
$$\epsilon_{ij} = C_{ijkl}\sigma_{kl}$$

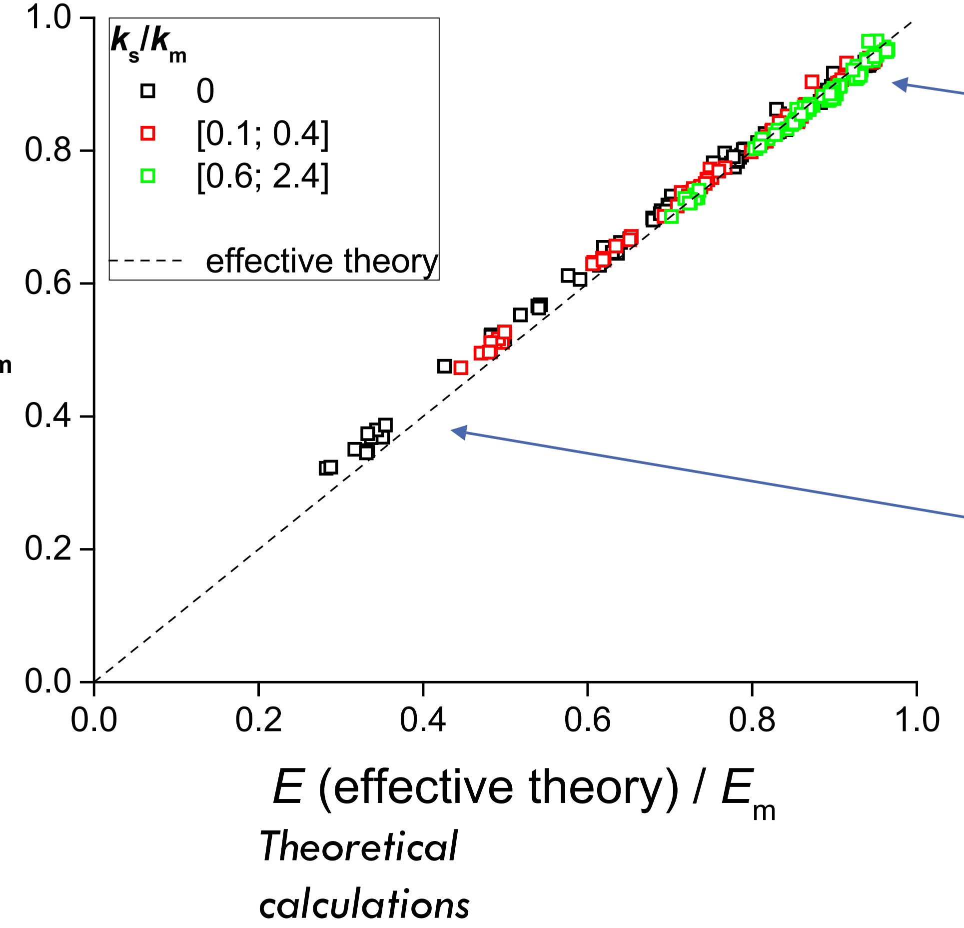
Davy et al., 2018, Elastic properties of fractured rock masses with frictional properties and power-law fracture size distributions: JGR, v. 123, p. 6521 - 6539.

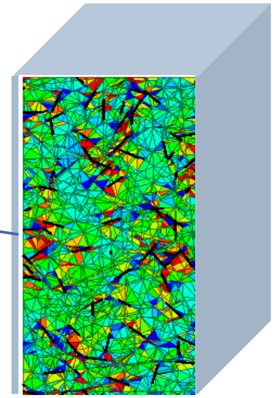
General case conditions :

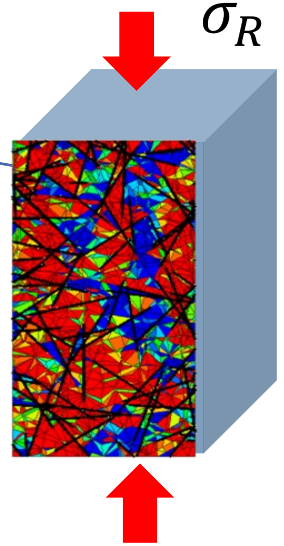
- **Shear displacement ($\boldsymbol{k_s}$)**
- **Effective theory to account for fracture interactions for large densities**
- Change of regime for critically stressed fractures (slipping, dilation)
- Normal displacement (k_n)

Comparison to numerical simulations



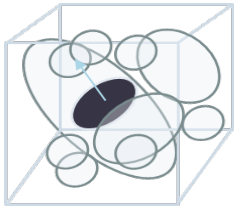


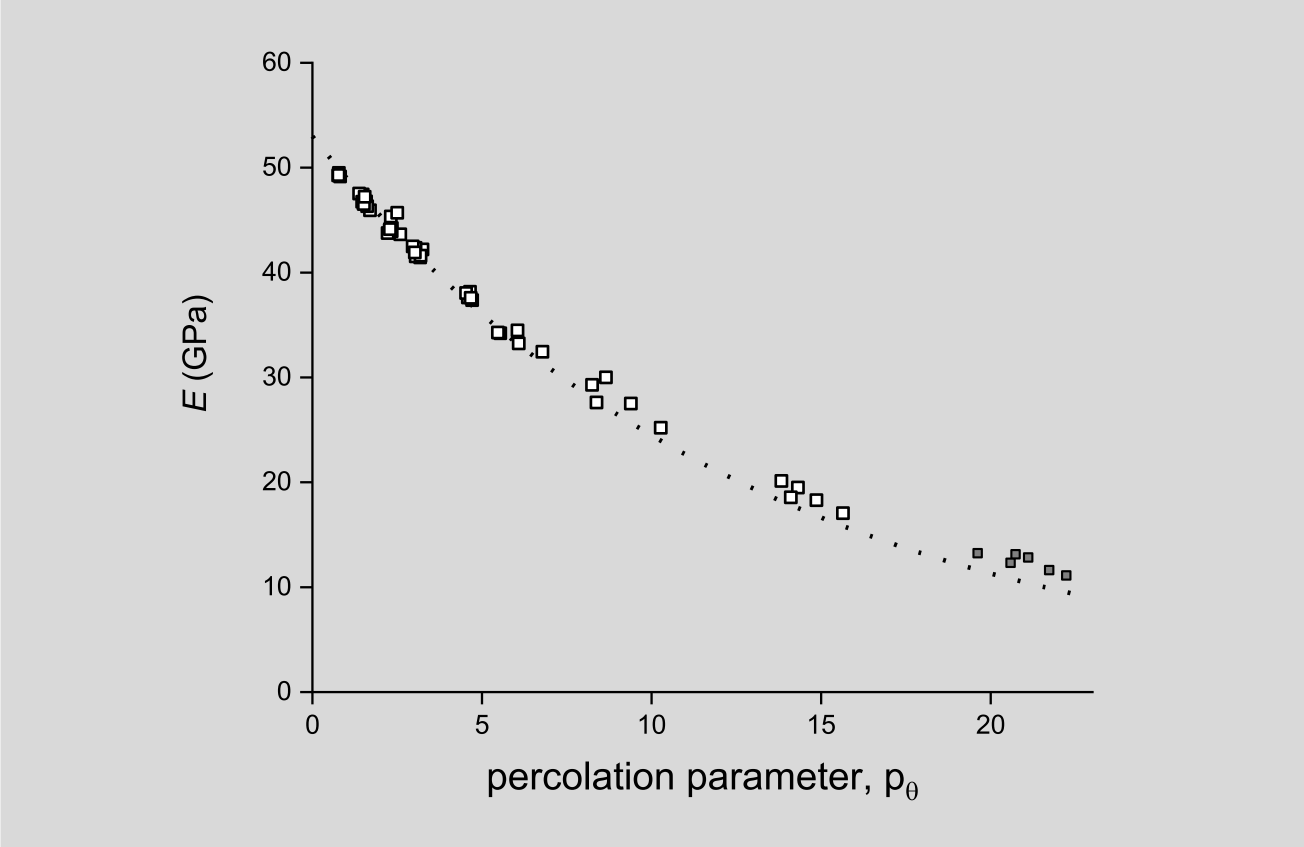




Predicting E_{eff} with analytical solutions for simple cases

$k_n \gg k_s = 0$





In this case, the DFN percolation parameter $p(\theta)$ is the controlling factor of the rockmass effective elastic modulus

$$E_{eff} = E_0 \exp(-c \cdot p(\theta))$$

$$p(\theta) = \frac{1}{V} \sum_f \left(\boldsymbol{l_f^3} \cos^2\theta_f \sin^2\theta_f \right)$$

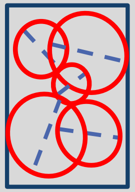
Predicting E_{eff} with analytical solutions for simple cases - $k_n \gg k_s$ constant

$$l_s = \frac{E_m}{k_s}$$

Over DFN range $l \ll l_s$

$$E_{eff} = E_m \exp(-c \cdot p(\theta))$$

$$p(\theta) = \frac{1}{V}\sum_f \left(l_f^3 \cos^2\theta_f \sin^2\theta_f\right)$$

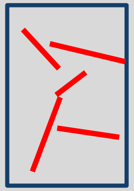


p – so called percolation parameter

Over DFN range $l \gg l_s$

$$E_{eff} = \frac{k_s}{P_{32}(\theta) + k_s/E_m}$$

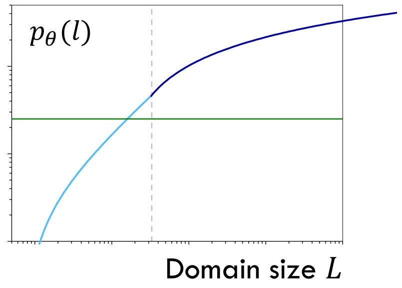
$$P_{32}(\theta) \sim \frac{1}{V}\sum_f l_f^2 \cos^2\theta_f \sin^2\theta_f$$



P_{32} total fracture surface per unit volume

Application to realistic multiscale DFN

Potential size effect since p is scale dependent

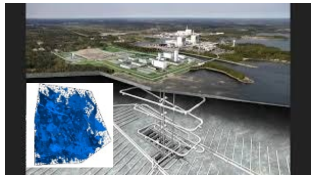


No size effect since P_{32} is scale independent

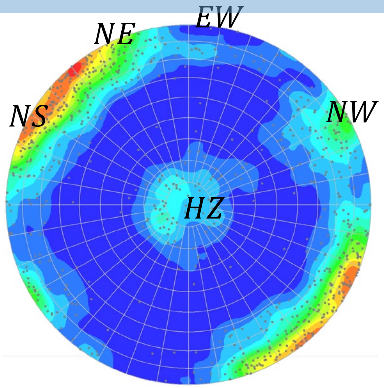
Application to site conditions – Forsmark case

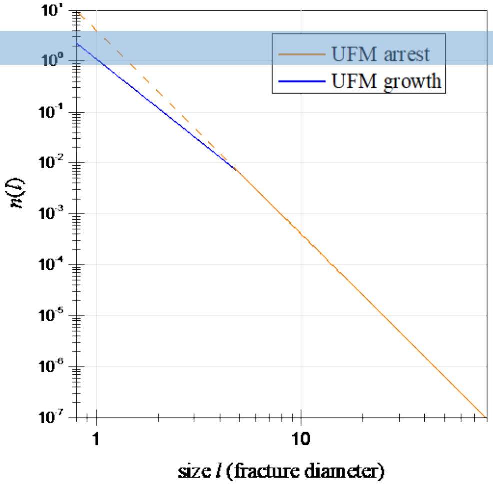
- Input : generated DFN
- Input : Intact rock properties
- Input : stress state
- Output:
  - Compliance tensor
  - Scale effect
  - Level of anisotropy

Application - DFN and rock conditions
SKB Forsmark site, Sweden

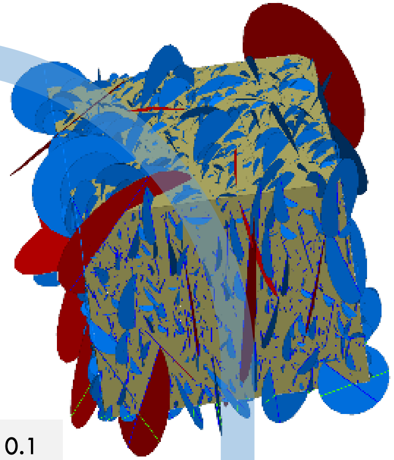


DFN (FFM01 unit)

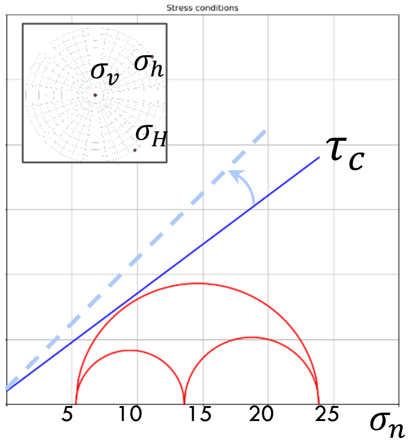




l_{min} = 0.1
L = 20



Mechanical properties



No critically stressed fractures

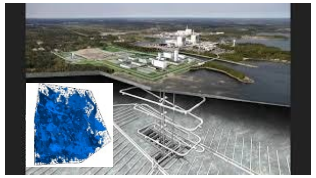
Intact Rock
$E_m = 76\ GPa$
$\nu_m = 0.23$

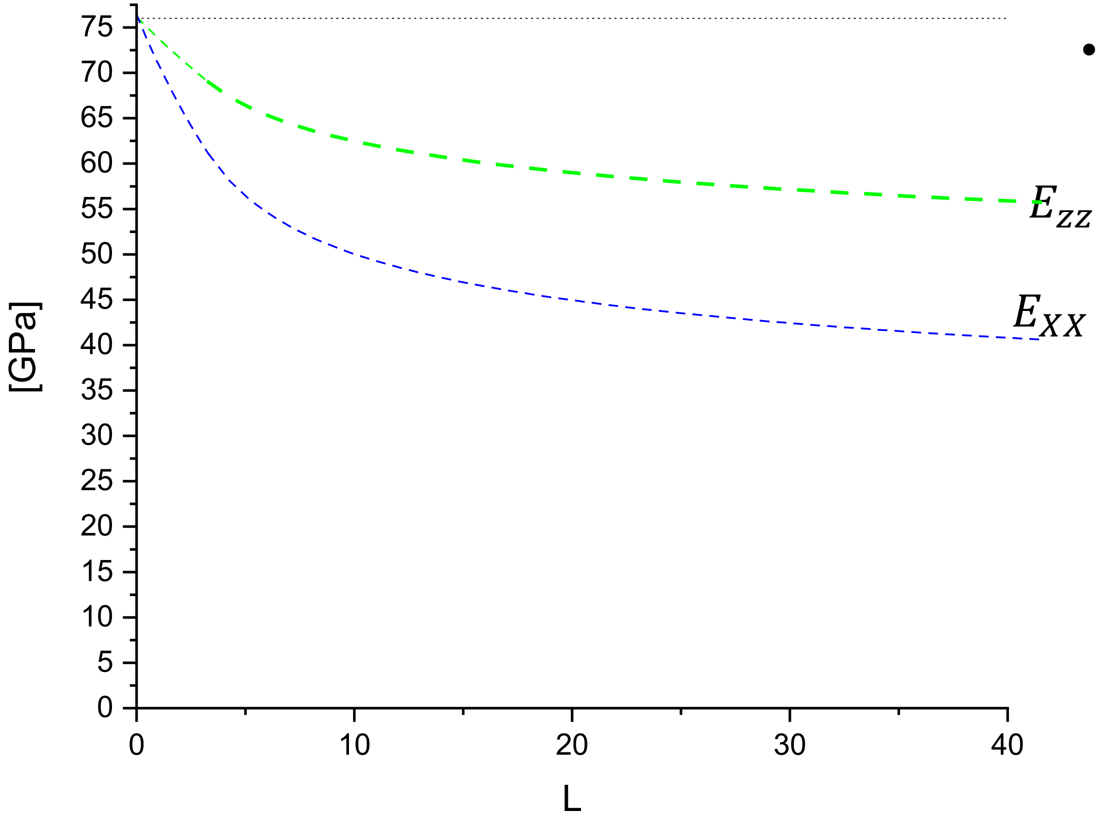
Fractures
$k_s(\sigma_n) = 46.55 \times \sigma_n^{0.4039} \times 10^6$
$k_n > 100 k_s$

$$\begin{bmatrix} \epsilon_x \\ \epsilon_y \\ \epsilon_z \\ \epsilon_{yz} \\ \epsilon_{xz} \\ \epsilon_{xy} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_{xx}} & -\frac{\nu_{yx}}{E_y} & -\frac{\nu_{zx}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{xy}}{E_x} & \frac{1}{E_y} & -\frac{\nu_{zy}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{xz}}{E_x} & -\frac{\nu_{yz}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{2G_{yz}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{2G_{xz}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2G_{xy}} \end{bmatrix} \times \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{bmatrix}$$

Compliance tensor $\overline{\overline{C}}$

Evolution of E_{ii} with L



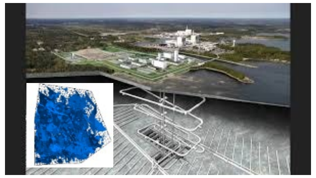


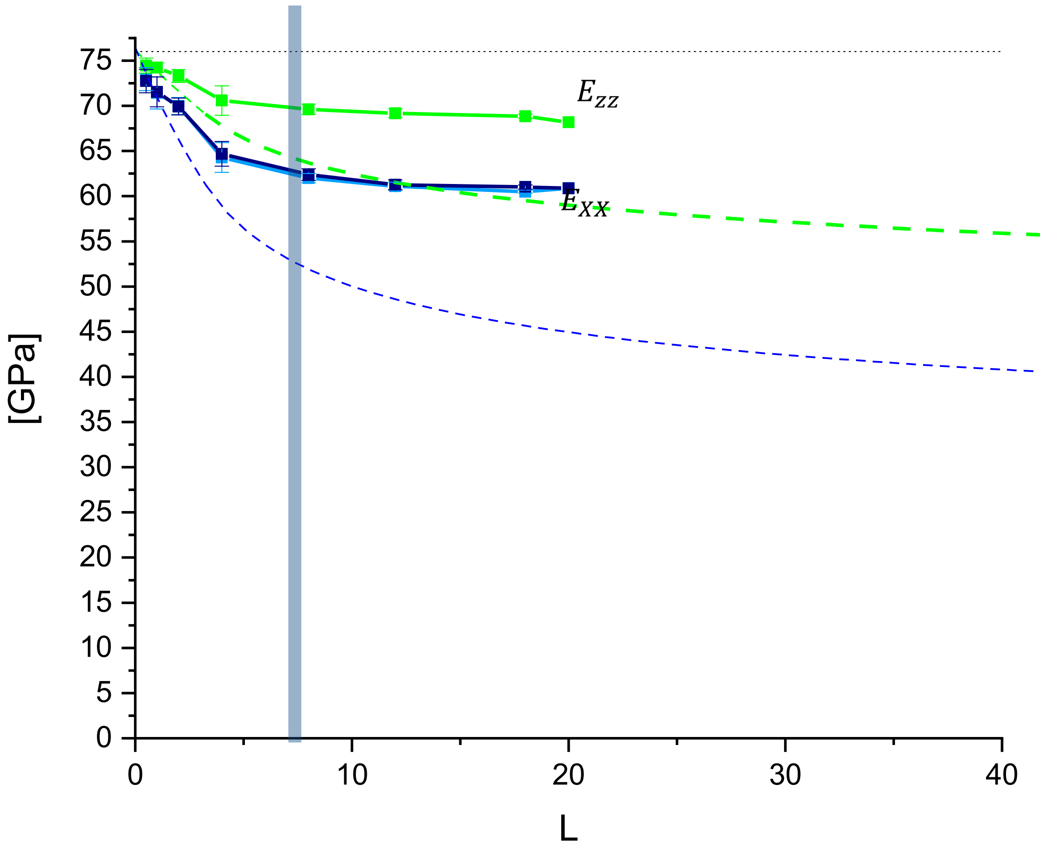
Increasing domain size L tend to put more large fractures without significantly changing P_{32}

Given the DFN conditions:

- If k_s such that $l \ll l_s$ → maximise the scaling effect

Evolution of E_{ii} with L





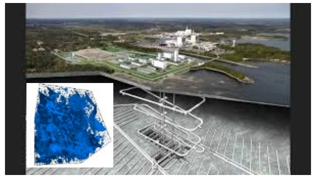
Given the DFN conditions:

- If k_s such that $l \ll l_m \rightarrow$ maximise the scaling effect

With current mechanical properties

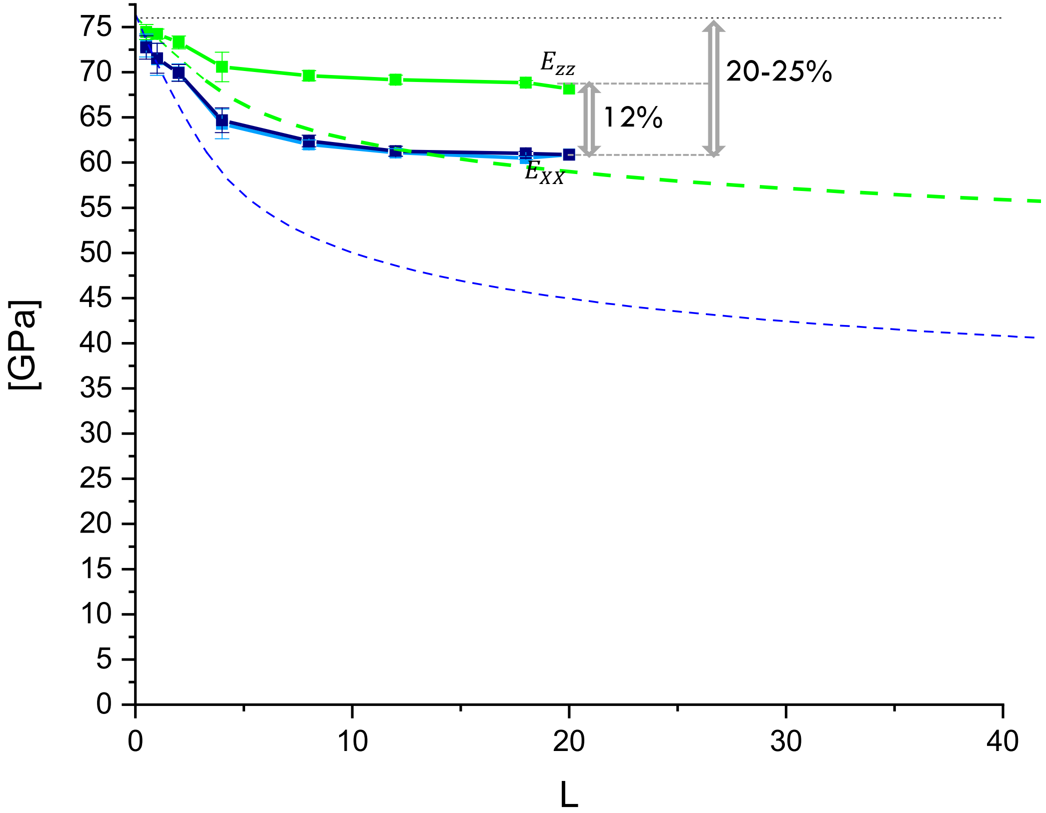
- $\langle k_s \rangle = 3.4e10$ GPa. m^{-1}
- 1.5 m $\leq l_s \leq 3.5$ m
- Decrease of E_{ii} with L up to ~10m.
- E_{xx} decrease from 76 Gpa to about 62 GPa, i.e. about 25%. *

Evolution of E_{ii} - Anisotropy



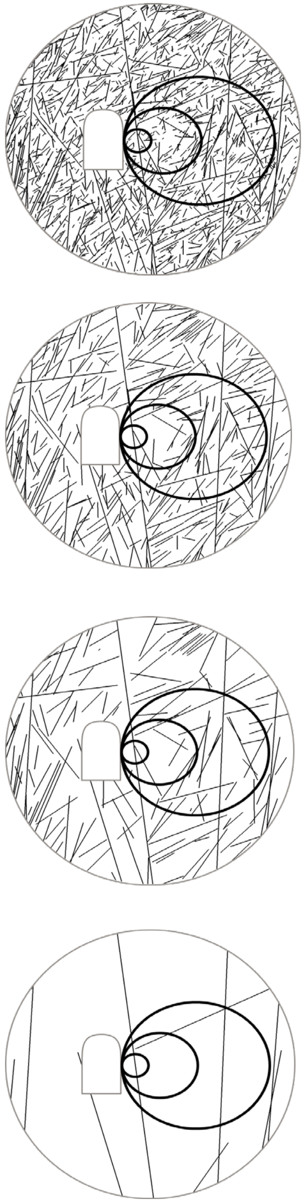
1 DFN

l_{min}	= 0.1
L	= 20
Ori	= FFM01
k_s	(σ_n)
k_n	$\approx \infty$



- E_{ii} variations : 60 to 70 Gpa (about 12%)
- E_{zz} less affected by fractures than horizontal E_{hz}
- (Horizontal directional E_{hz} consistent with fracture sets NE and NW, less affected by fracture shearing are at trend 45°)

SUMMARY



- DFN representation of rockmass help to integrate multiscale fracture distribution
- Rockmass effective properties can be derived and controlling factors – as a combination between mechanical, geometrical and scale - identified
- Extent of scale effect and anisotropy can be quantified
- Tool (DFN.lab) to integrate DFN in geomechanical models

DFN.lab Numerical platform for modelling fractured media