

Estimating rock mass effective elastic properties from a Discrete Fracture Network (DFN) approach



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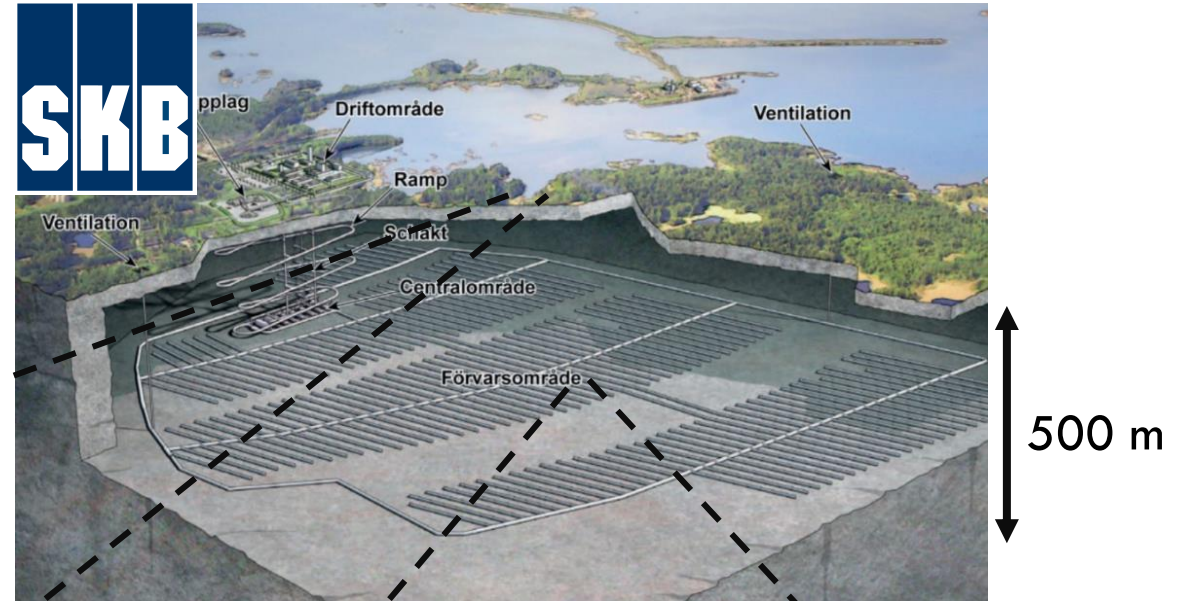


CFMR
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DE MÉCANIQUE
DES ROCHES

Introduction

Context

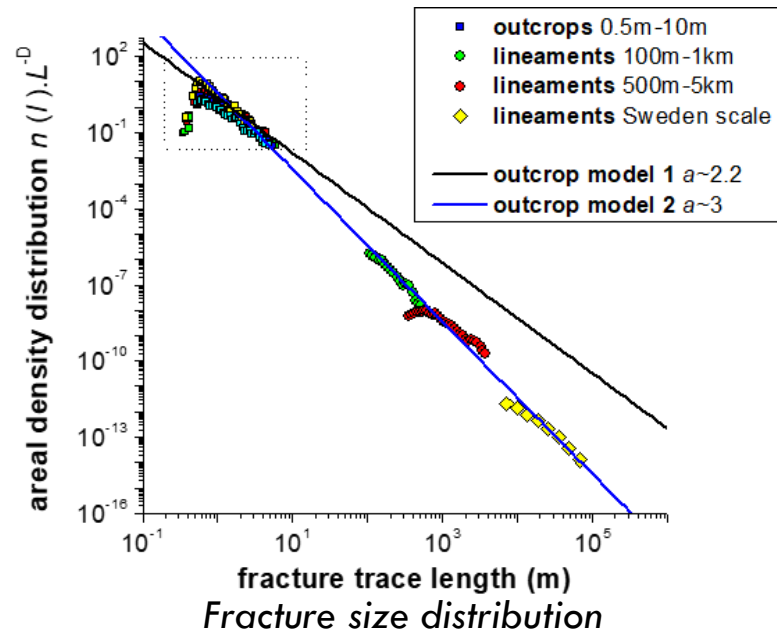
- Nuclear waste storage
- Crystalline rocks
- Fracture networks
- Hydrogeology
- Geomechanics



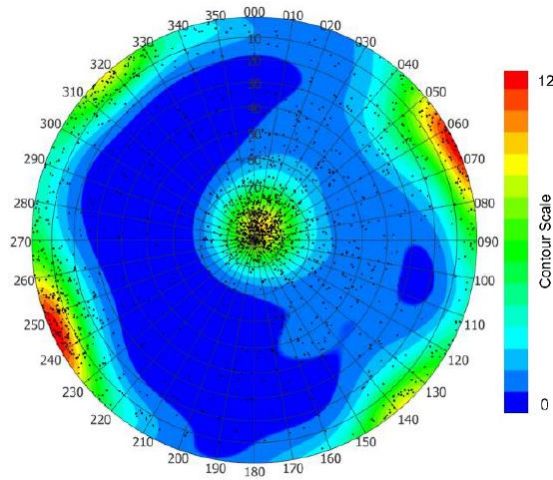
Introduction

Challenges

- Scale
 - Multiscale fracture networks (cm → km)
 - REV ?



- Anisotropy
 - Several fracture sets
 - Orientation distributions



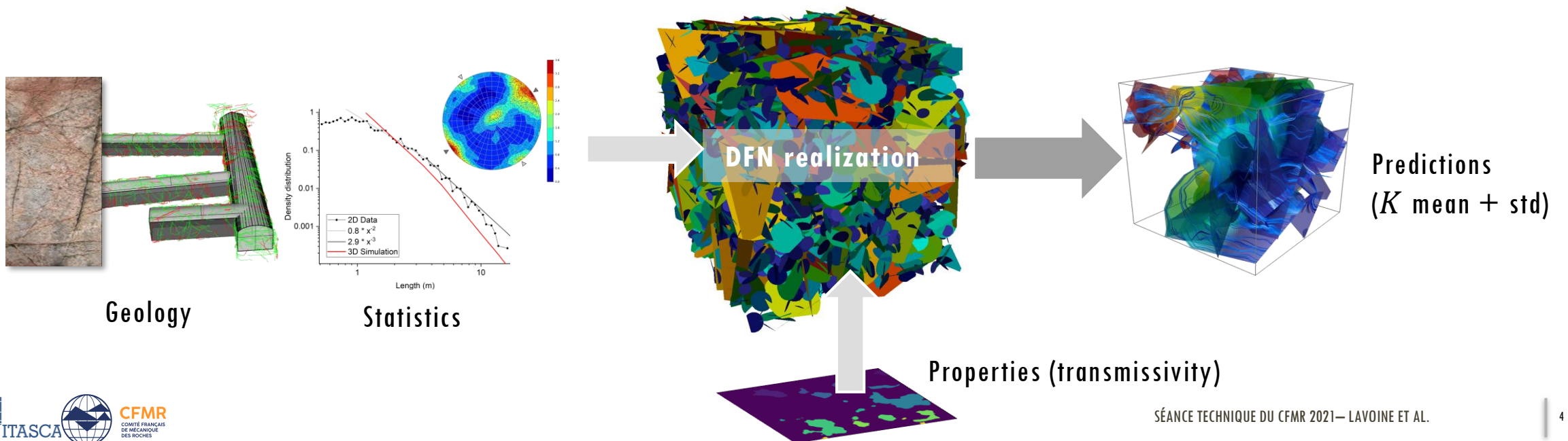
- ⇒ Fractures should be a central point of rock mass (RM) modelling
- ⇒ DFN methodology

Introduction

The Discrete Fracture Network (DFN) methodology [Selroos et al., 2021]

Fractured RM: population of deterministic and stochastic fracture-like objects embedded in an impervious elastic matrix

- Integrate geological, hydrogeological and mechanical data
- Valid regardless of fracture density
- Basis for simplification: effective properties, main hydro paths...
- And understanding: link with global indicators (percolation parameter...)



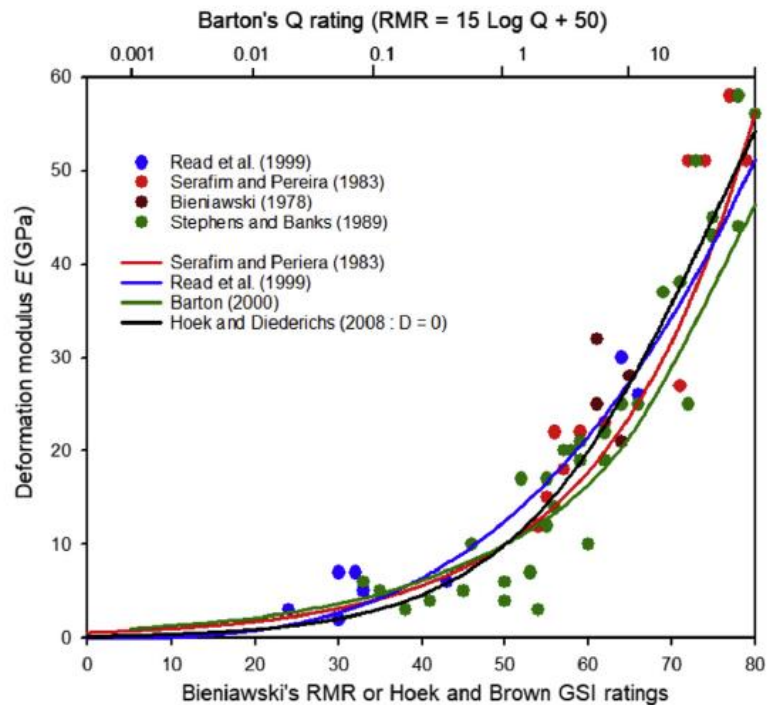
Applying the DFN methodology in geomechanics

To estimate fractured RM effective elastic properties

Introduction

Classically

- Rock Mass Classification (RMC) charts
- RQD, Q, RMR, GSI, D...
- Semi-empirical relationships



[Hoek and Brown (2018)]

GEOLOGICAL STRENGTH INDEX FOR JOINTED ROCKS (Hoek and Marinos, 2000)

From the lithology, structure and surface conditions of the discontinuities, estimate the average value of GSI. Do not try to be too precise. Quoting a range from 33 to 37 is more realistic than stating that GSI = 35. Note that the table does not apply to structurally controlled failures. Where weak planar structural planes are present in an unfavourable orientation with respect to the excavation face, these will dominate the rock mass behaviour. The shear strength of surfaces in rocks that are prone to deterioration as a result of changes in moisture content will be reduced if water is present. When working with rocks in the fair to very poor categories, a shift to the right may be made for wet conditions. Water pressure is dealt with by effective stress analysis.

SURFACE CONDITIONS	DECREASING SURFACE QUALITY →			
	VERY GOOD Very rough, fresh unweathered surfaces	GOOD Rough, slightly weathered, iron stained surfaces	FAIR Smooth, moderately weathered and altered surfaces	VERY POOR Slackensided, highly weathered surfaces with soft clay coatings or fillings
STRUCTURE				
INTACT OR MASSIVE - intact rock specimens or massive in situ rock with few widely spaced discontinuities	90		N/A	N/A
BLOCKY - well interlocked undisturbed rock mass consisting of cubical blocks formed by three intersecting discontinuity sets	80	70		
VERY BLOCKY- interlocked, partially disturbed mass with multi-faceted angular blocks formed by 4 or more joint sets		60	50	
BLOCKY/DISTURBED/SEAMY - folded with angular blocks formed by many intersecting discontinuity sets. Persistence of bedding planes or schistosity			40	30
DISINTEGRATED - poorly interlocked, heavily broken rock mass with mixture of angular and rounded rock pieces				20
LAMINATED/SHEARED - Lack of blockiness due to close spacing of weak schistosity or shear planes	N/A	N/A		10

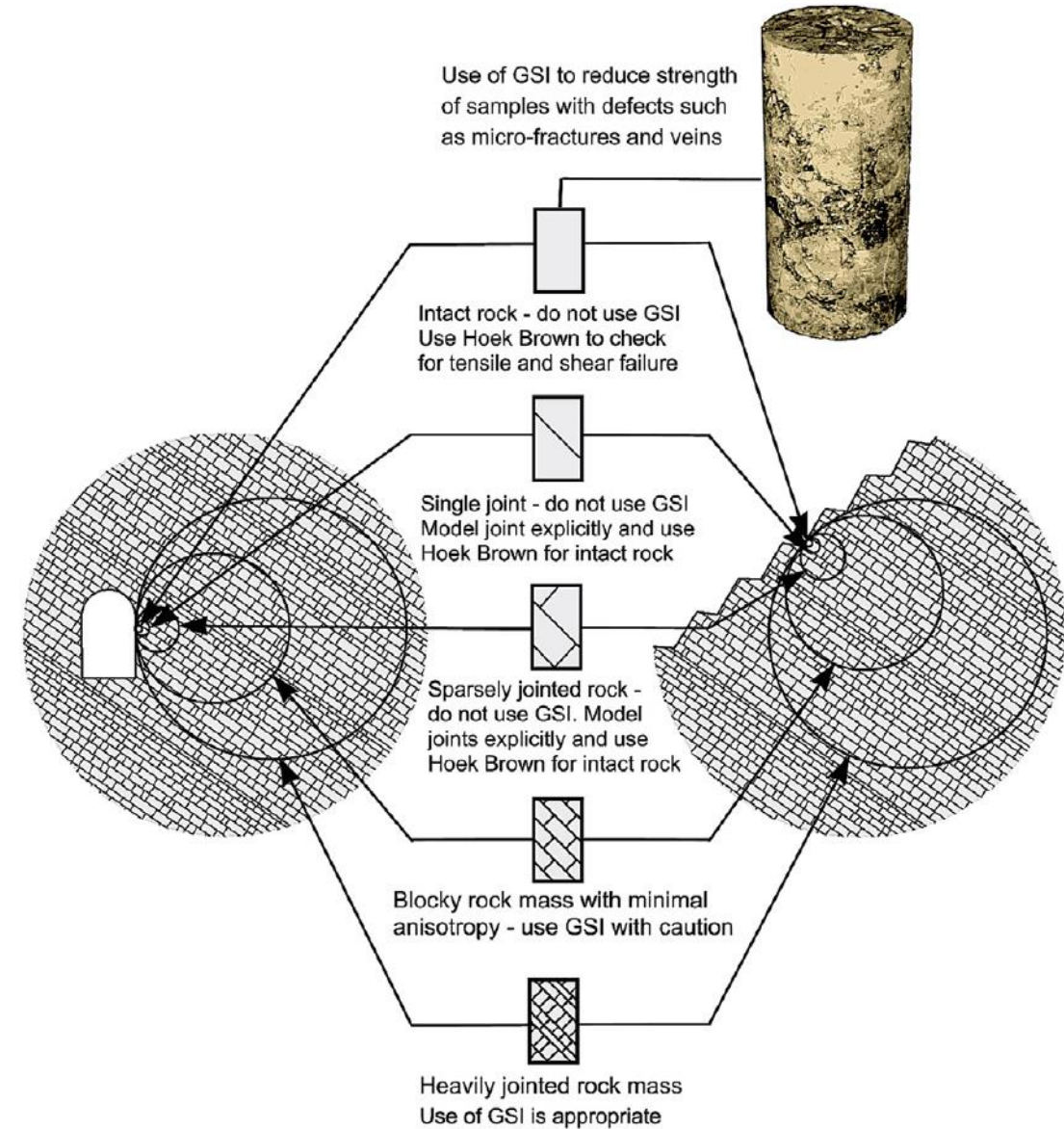
DECREASING INTERLOCKING OF ROCK PIECES ↓

[Hoek and Marinos (2000)]

Introduction

Adapted to heavily jointed rock masses

- Assembly of blocks
- Several sets of potentially infinite fractures
- Defined by fracture spacing only
- Applicable when model resolution \gg spacing



[Hoek and Brown (2018)]

Introduction

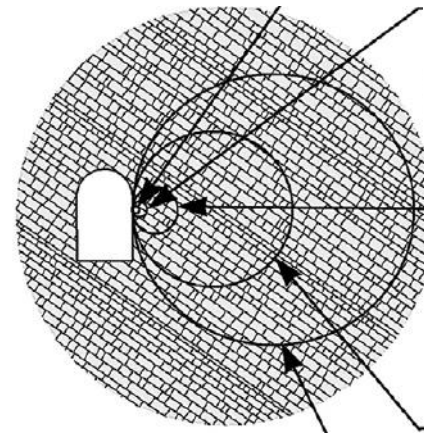
Adapted to heavily jointed rock masses

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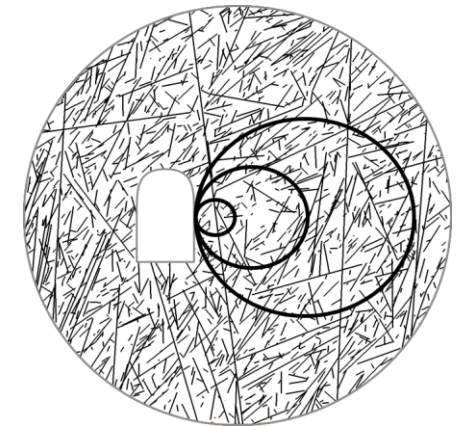
Lack of

- 3D representation
- Scale
- Anisotropy

⇒ DFN methodology



Block assembly



Population of individual fractures

Introduction

Objectives

- Overcome limitations of classical RMC approaches
- Using the DFN methodology to estimate RM effective elastic properties quantitatively

Effective compliance tensor $\bar{\bar{\bar{C}}} = \bar{\bar{\bar{\epsilon}}} : \bar{\bar{\bar{\sigma}}}^{-1}$

→ Total rock mass deformation

- Define which DFN metric is the controlling factor

Fractures contribution to rock deformation

Total rock mass deformation : matrix deformation + contribution of all fractures

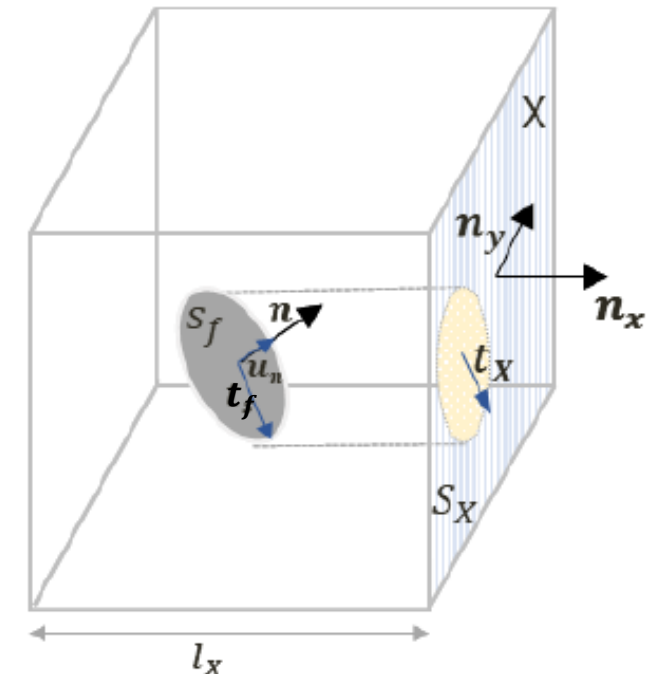
$$\epsilon_{ij} = C_{ijkl}^0 \sigma_{ij}^R + \sum_f (\epsilon_{ij})_f$$

Contribution of fracture f to the deformation component ϵ_{xy}

$$(\epsilon_{xy})_f = \frac{t_x \cdot n_y}{l_x} \longrightarrow \text{Displacement / length}$$

$$t_x = (n \cdot n_x) \frac{\int_{S_f} t_f \cdot dS}{S_x}$$

contribution of the fracture f to the displacement to the x boundary is obtained by projecting and integrating the displacement field on the x boundary



Fractures contribution to rock deformation

Total rock mass deformation : matrix deformation + contribution of all fractures

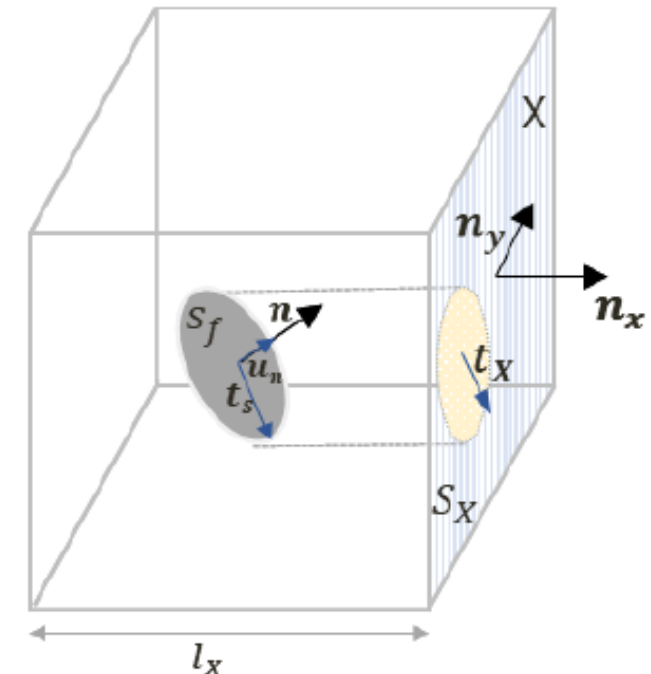
$$\epsilon_{ij} = C_{ijkl}^0 \sigma_{ij}^R + \sum_f (\epsilon_{ij})_f$$

Contribution of fracture f to the deformation component ϵ_{xy}

$$(\epsilon_{xy})_f = (\mathbf{n} \cdot \mathbf{n}_x) \frac{S_f}{V} (\bar{\mathbf{t}}_f \cdot \mathbf{n}_y)$$

The equation is annotated with arrows pointing to:

- $(\mathbf{n} \cdot \mathbf{n}_x)$: Rock volume
- $\frac{S_f}{V}$: Fracture surface
- $(\bar{\mathbf{t}}_f \cdot \mathbf{n}_y)$: mean shear fracture displacement (circled in red)



Fractures contribution to rock deformation

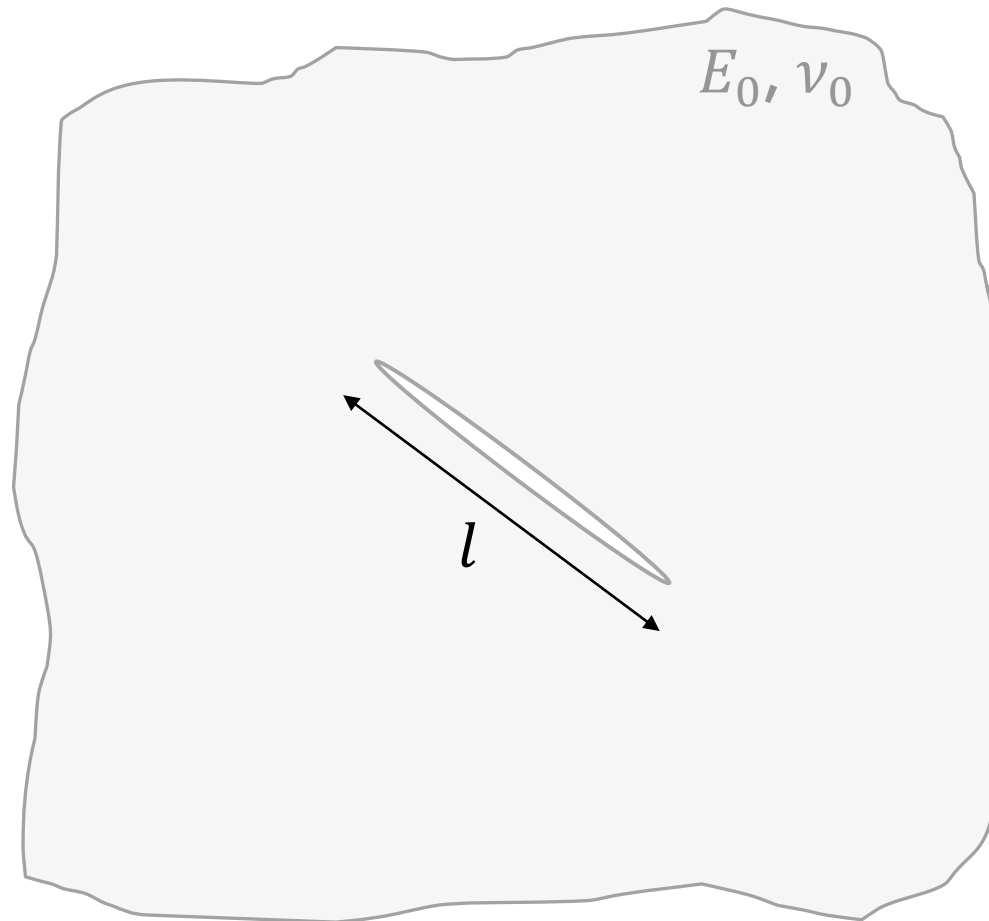
Mean shear displacement

Fracture of size l

Elastic matrix

Intact Young modulus E_0

Intact Poisson ratio ν_0



Fractures contribution to rock deformation

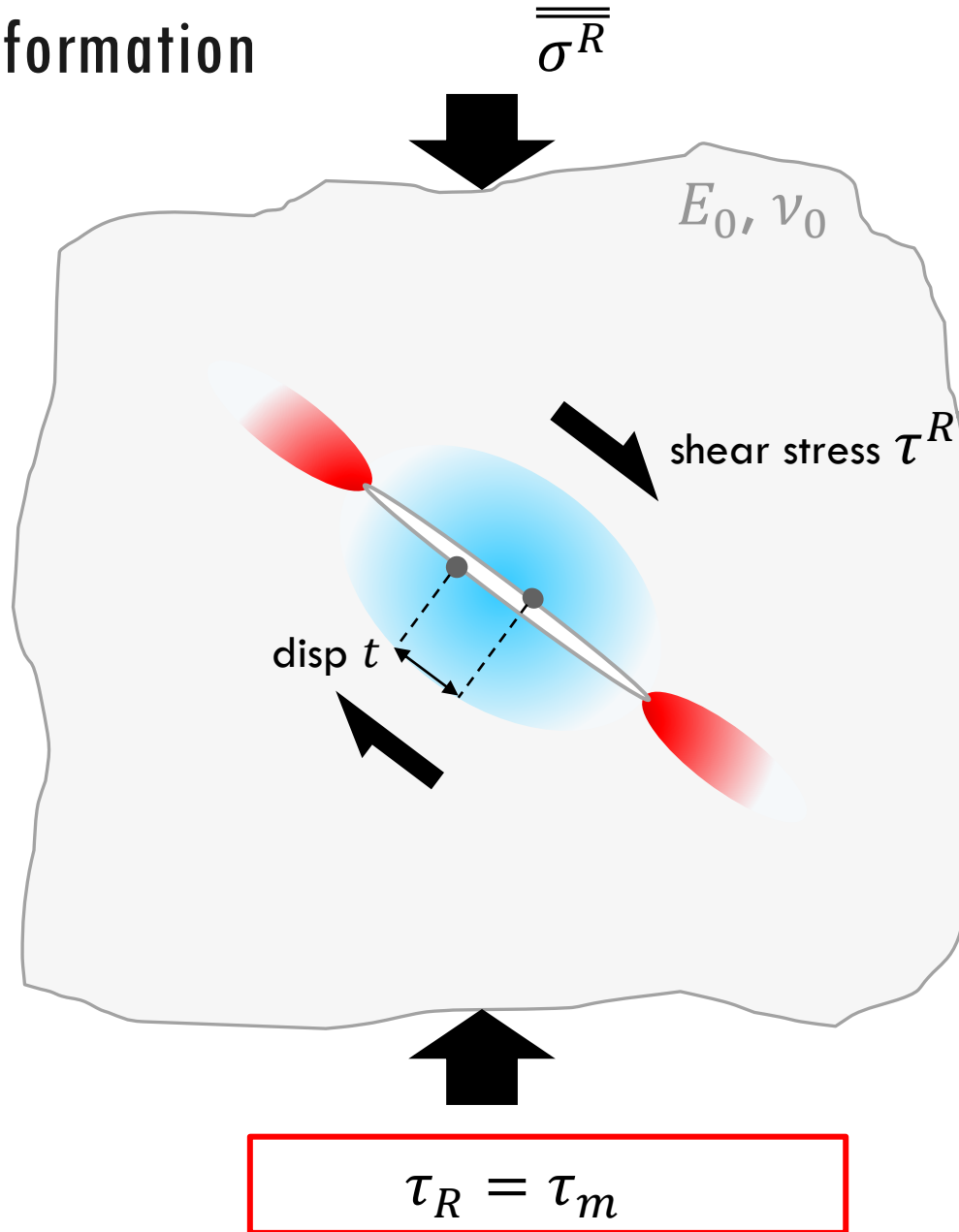
Mean shear displacement

Matrix resistance to deformation

$$\tau_m = k_m \cdot t$$

$$k_m = \frac{3\pi}{8} \cdot \frac{1 - \nu_0/2}{1 - \nu_0^2} \cdot \frac{E_0}{l} = \frac{E_m^*}{l}$$

Poisson ratio
Intact rock modulus
Fracture size



Fractures contribution to rock deformation

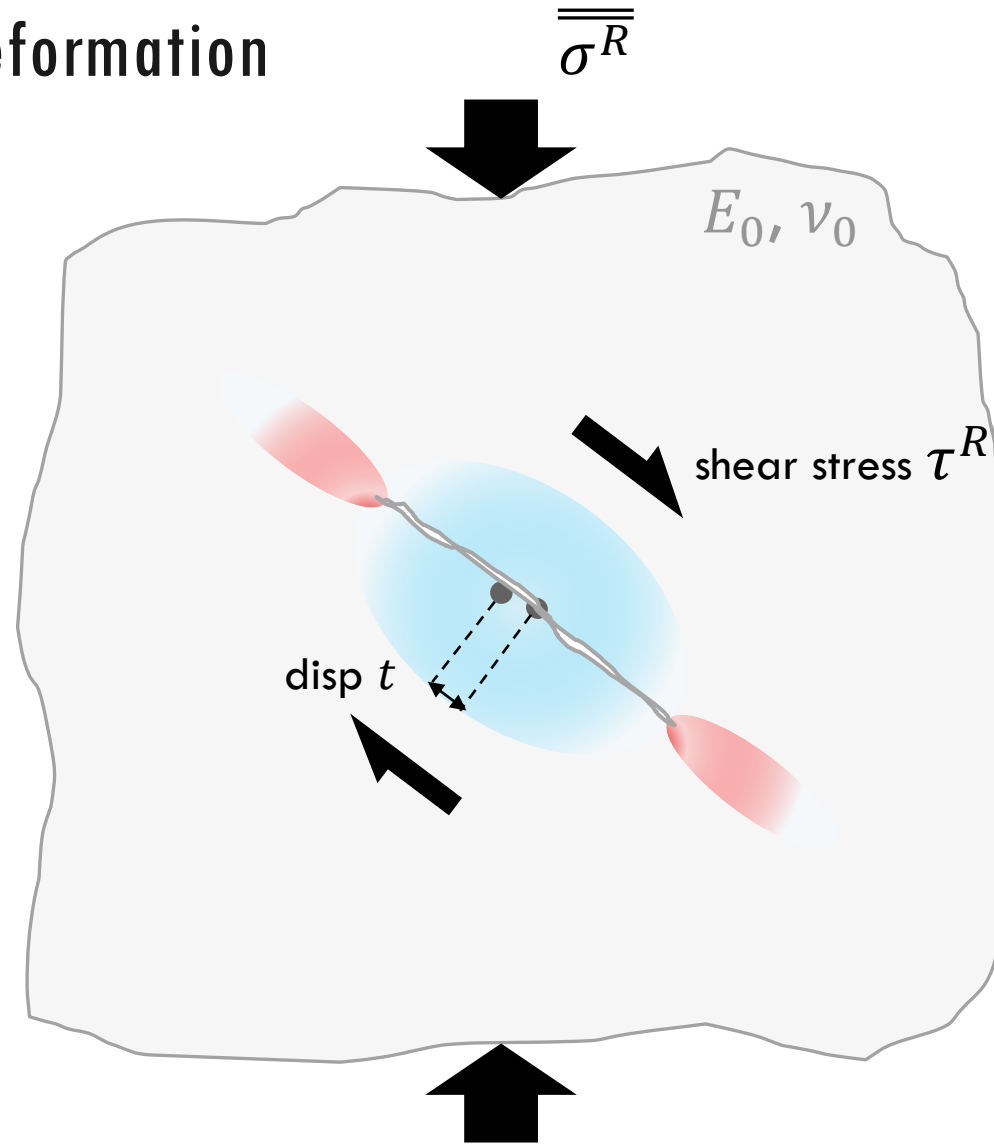
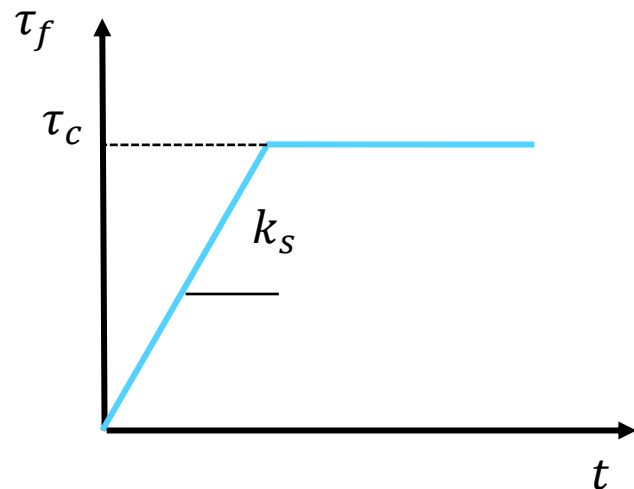
Mean shear displacement

Fracture plane resistance

$$\tau_f = \min(k_s \cdot t, \tau_c)$$

Fracture shear stiffness

Coulomb stress limit
(if critically stressed)

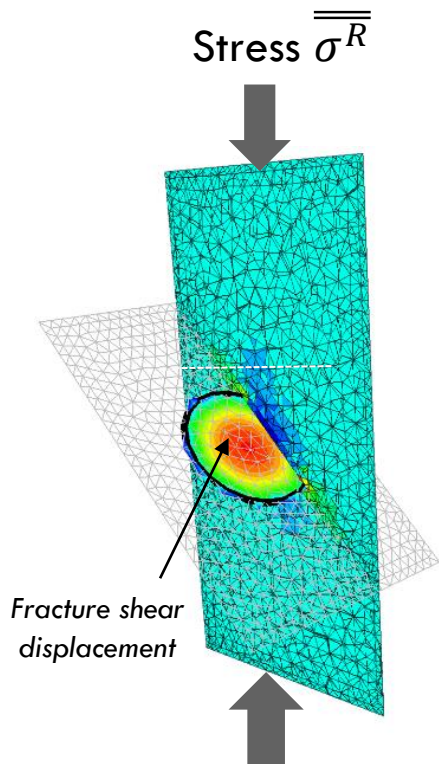


$$\tau_R = \tau_m + \tau_f$$

Stress partitioning

Fractures contribution to rock deformation

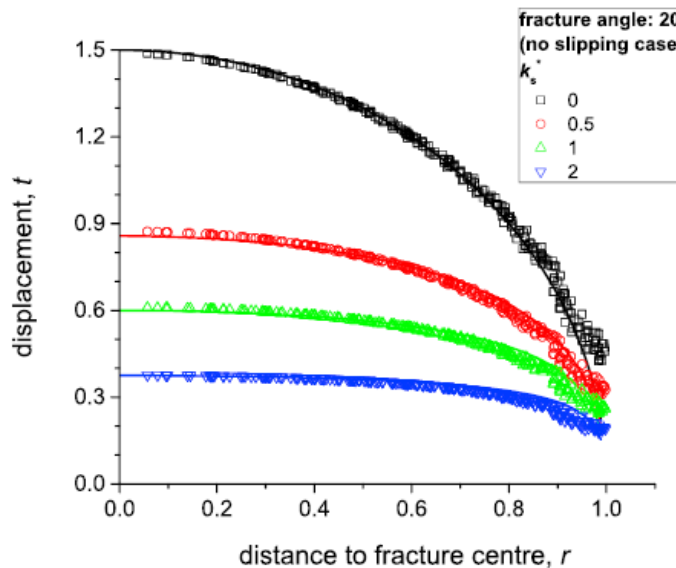
Mean shear displacement



average

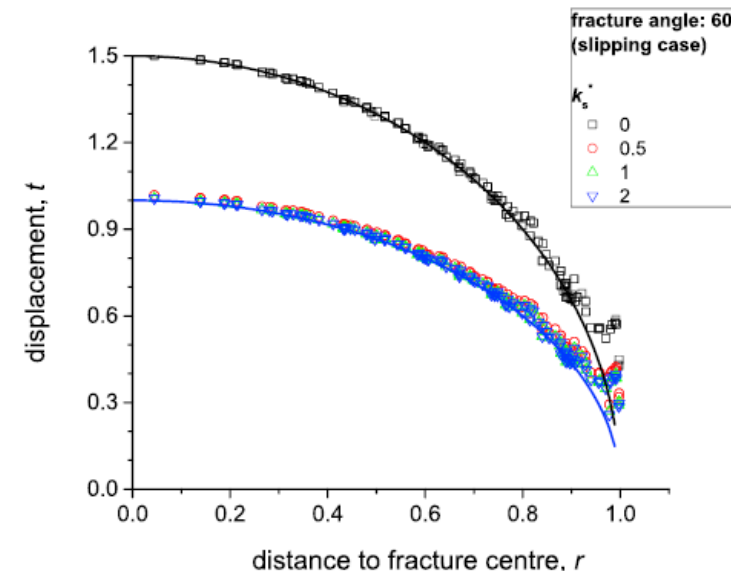
If not critically stressed

$$\frac{\tau^R}{t(r)} = \frac{\frac{2}{3}k_m}{\sqrt{1 - \left(\frac{2r}{l}\right)^2}} + k_s$$



If critically stressed

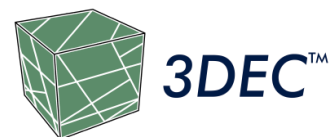
$$\frac{\tau^R - \tau_c}{t(r)} = \frac{\frac{2}{3}k_m}{\sqrt{1 - \left(\frac{2r}{l}\right)^2}}$$



[Davy et al. (2018)]

$$\bar{t} = \frac{\tau^R}{k_m + k_s}$$

$$\bar{t} = \frac{\tau^R - \tau_c}{k_m}$$



Fractures contribution to rock deformation

Scale dependency

With $l_s = \frac{E_m^*}{k_s}$, the fracture size so that $k_m = k_s$

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



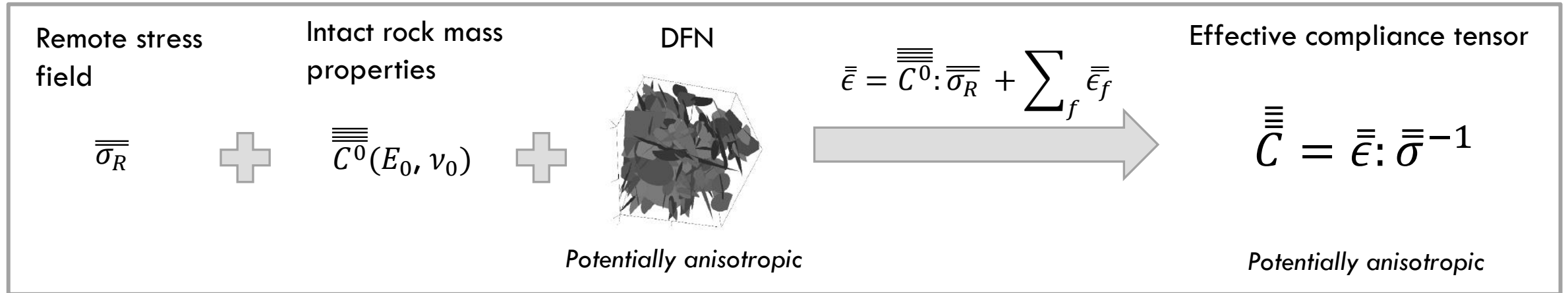
If k_s is negligible, fracture size defines the shear displacement

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



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

Effective rock mass elastic properties



Effective Theory:

Fracture f « sees » a matrix damaged by $[1, (f - 1)]$ fractures

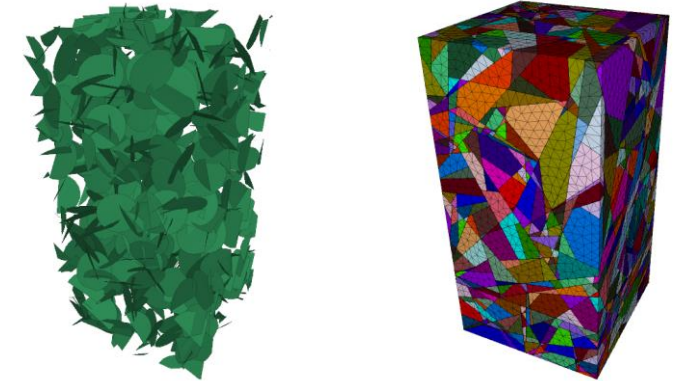
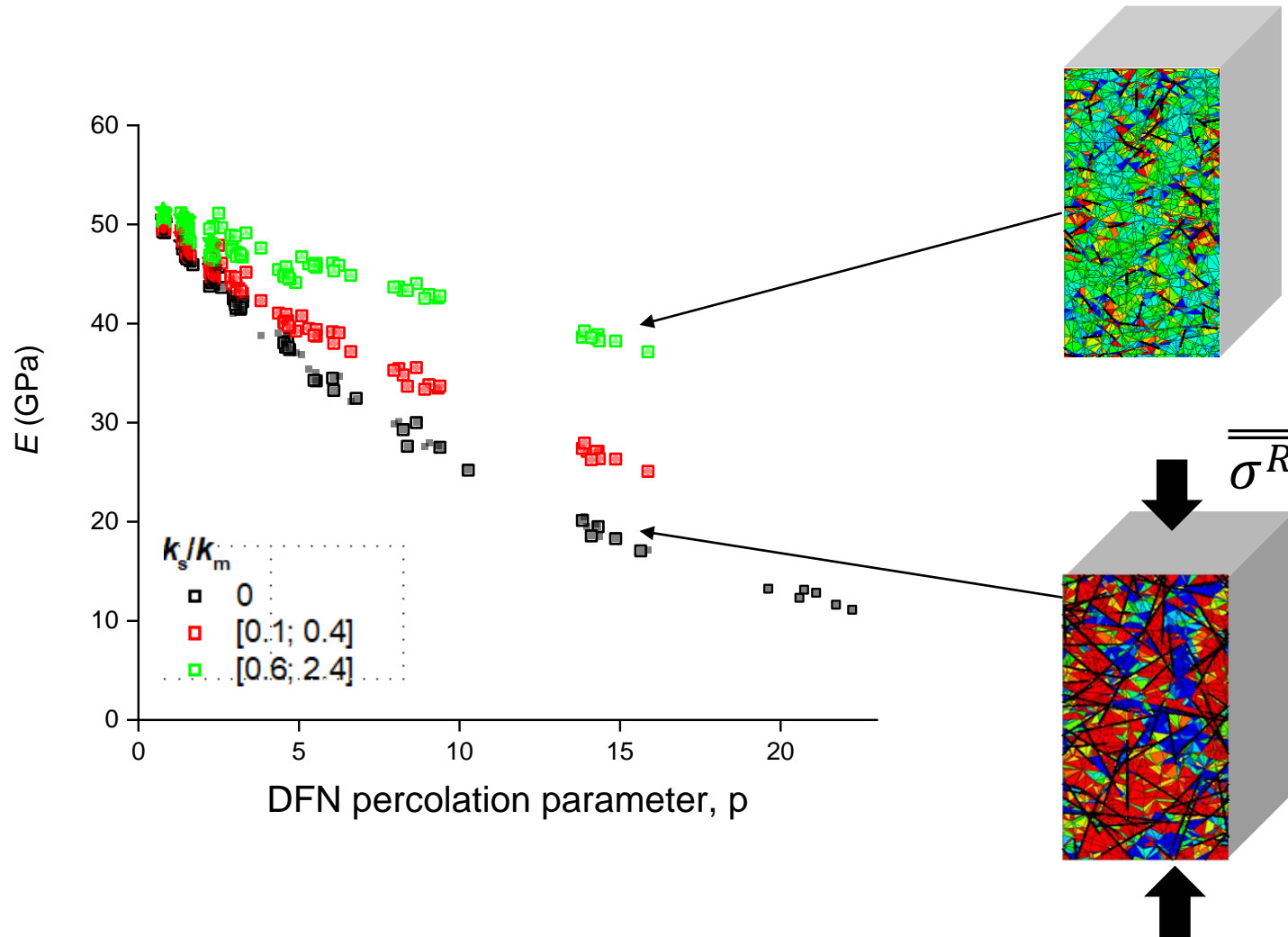
Loop for all fractures

$$E_{f-1} = \frac{1}{3} \left(\frac{1}{E_{xx,f-1}} + \frac{1}{E_{xx,f-1}} + \frac{1}{E_{xx,f-1}} \right)$$

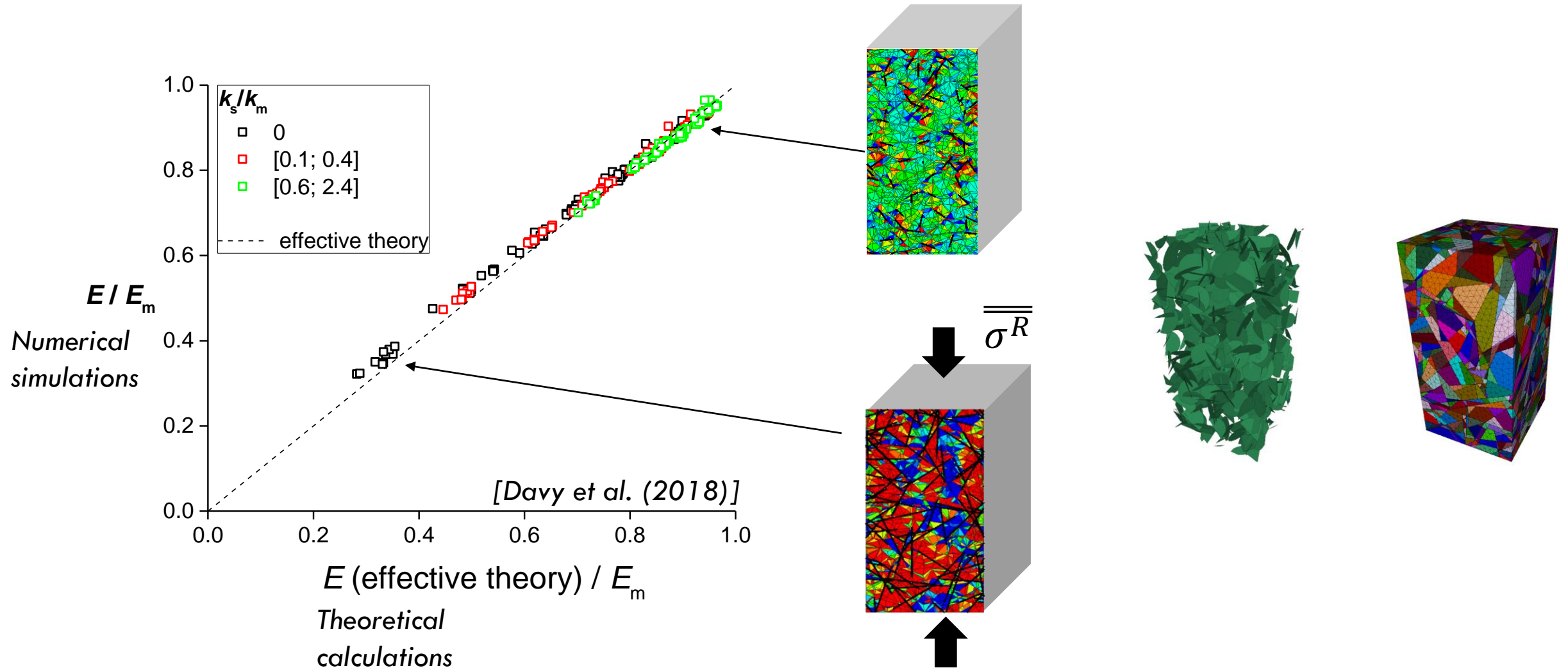
$$t_f = \frac{\tau}{k_s + \frac{E_{f-1}^*}{l_f}}$$

$$E_{xx,f}, E_{yy,f}, E_{zz,f}$$

Effective rock mass elastic properties



Effective rock mass elastic properties



Effective rock mass elastic properties

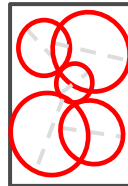
Analytical solutions for simple cases

- If $k_s \ll k_m$ ($l \ll l_s$)

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

$$p = \frac{1}{V} \sum_f l_f^3$$

So-called percolation parameter



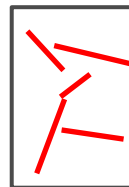
Potential size effect since p is scale dependent

- If $k_s \gg k_m$ ($l \gg l_s$)

$$E_{eff} \sim \frac{k_s}{P_{32} + k_s/E_m}$$

$$P_{32} = \frac{1}{V} \sum_f l_f^2$$

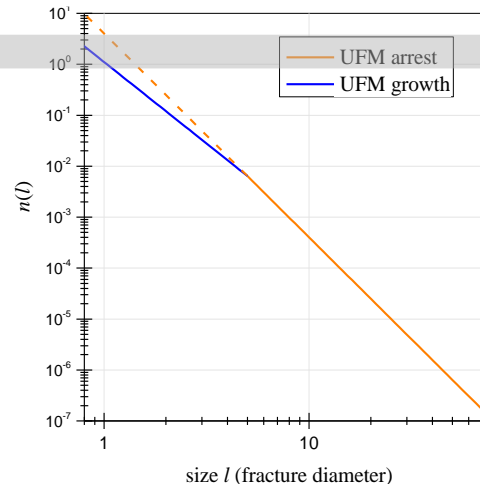
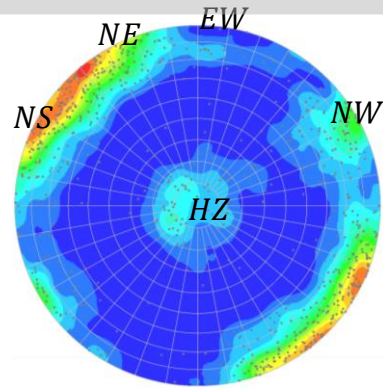
Total fracture surface per unit volume



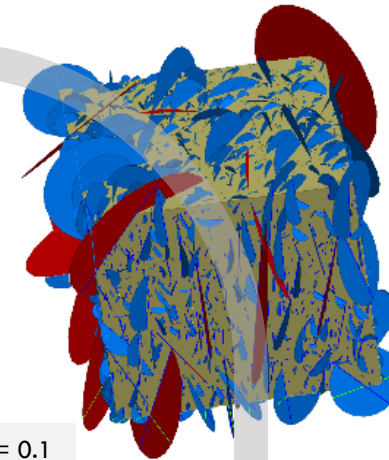
No size effect since P_{32} is scale independent

Application to Forsmark FFM01 deformation zone

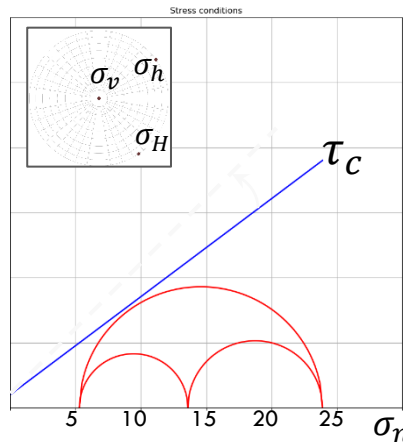
DFN (FFM01 unit)



l_{min} = 0.1
 L = 20



Mechanical properties



No critically stressed fractures

Intact Rock

$$E_m = 76 \text{ GPa}$$

$$\nu_m = 0.23$$

Fractures

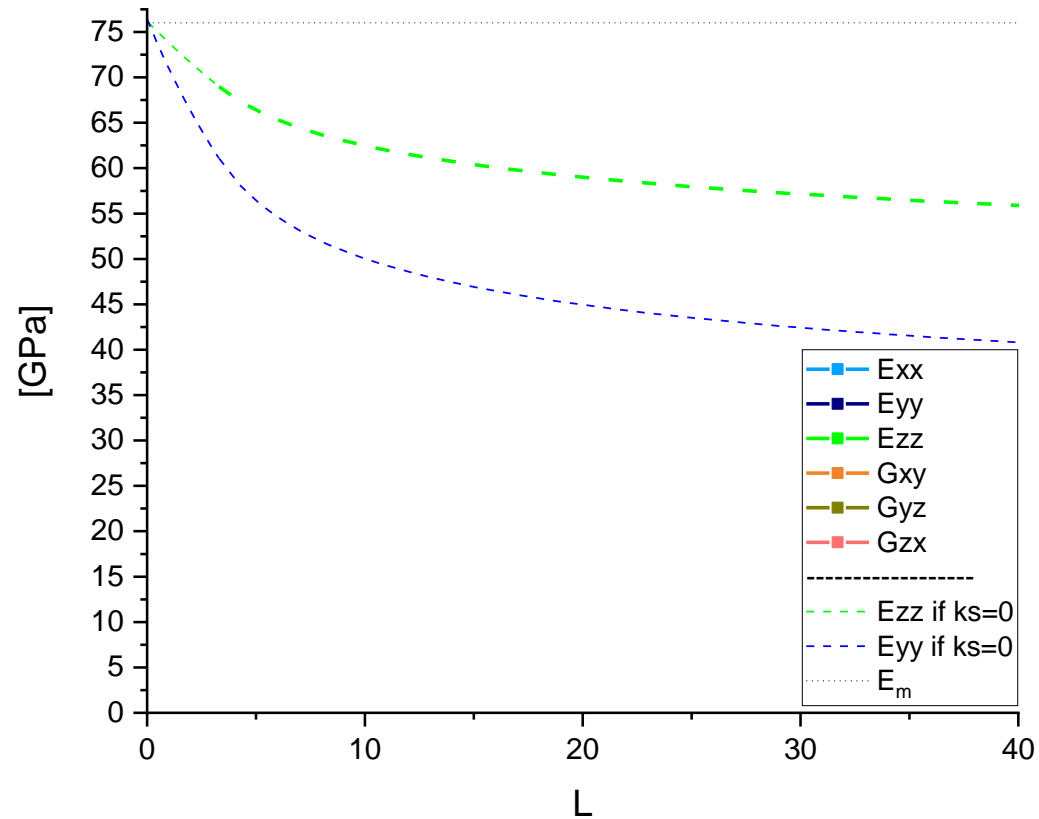
$$k_s(\sigma_n) = 46.55 \times \sigma_n^{0.4039} \times 10^6$$

$$k_n > 100k_s$$

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

Compliance tensor $\bar{\bar{C}}$

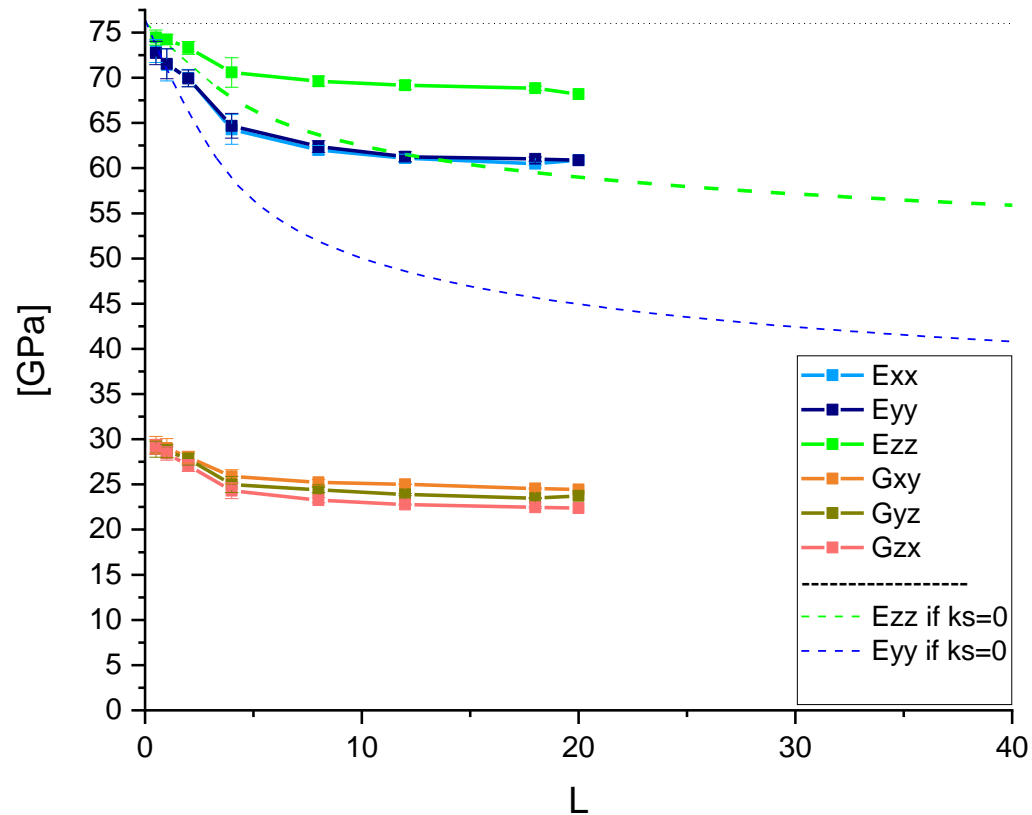
Application to Forsmark FFM01 deformation zone



Given the DFN conditions:

- If $k_S = 0 \rightarrow$ maximise the scaling effect

Application to Forsmark FFM01 deformation zone



Given the DFN conditions:

- If $k_s = 0 \rightarrow$ maximise the scaling effect

With current mechanical properties

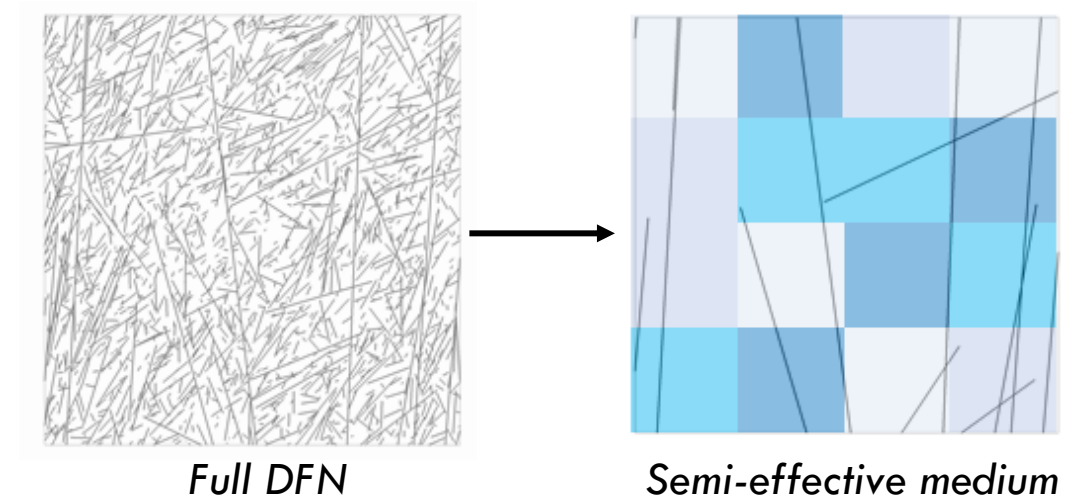
- $1.5 \text{ m} \leq l_s \leq 3.5 \text{ m}$
- Decrease of E_{ii} with L up to $\sim 10\text{m}$.
- E_{xx} decrease from 76 GPa to about 62 GPa, i.e. about 25%.

Conclusion

- DFN methodology: integrate multiscale anisotropic fracture distributions
- Effective elastic properties of fractured RM can be assessed quantitatively by a method combining individual fractures contributions
- The developed method can be applied to large DFN (million of fractures)
- Fracture frictional properties introduce scales effects
- Depending on fracture frictional properties (ratio l/l_s) the effective properties are driven either by p or P_{32}

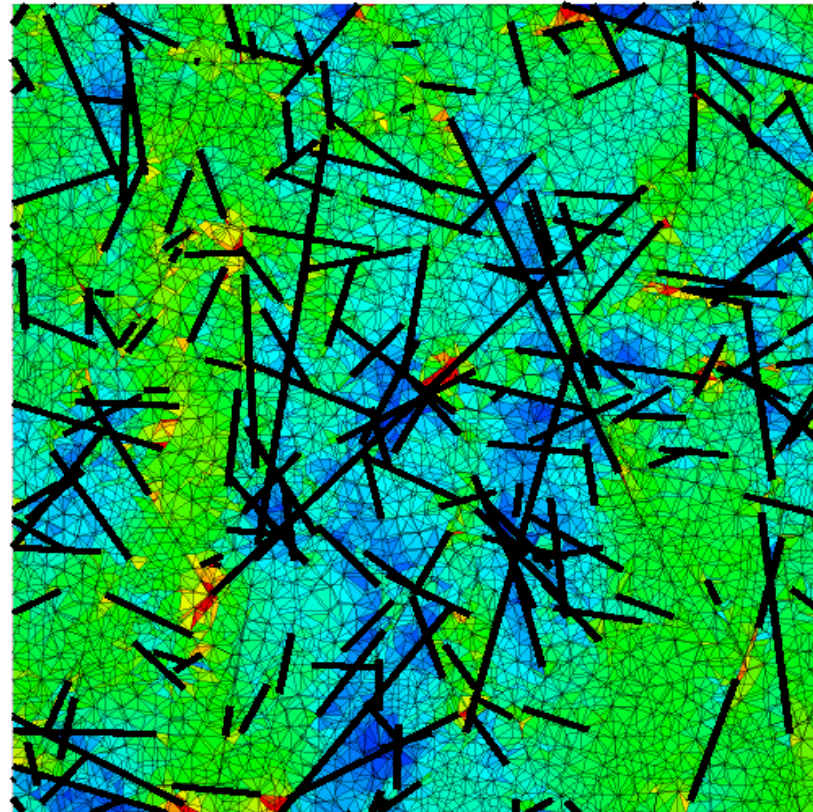
Perspective

- Comparison with predictions based on RMC charts
- Characterization of stress fluctuations, and associated scale dependence
- Semi-effective medium representation
- Extend the methodology to strength properties



Conclusion

Thanks for your attention



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