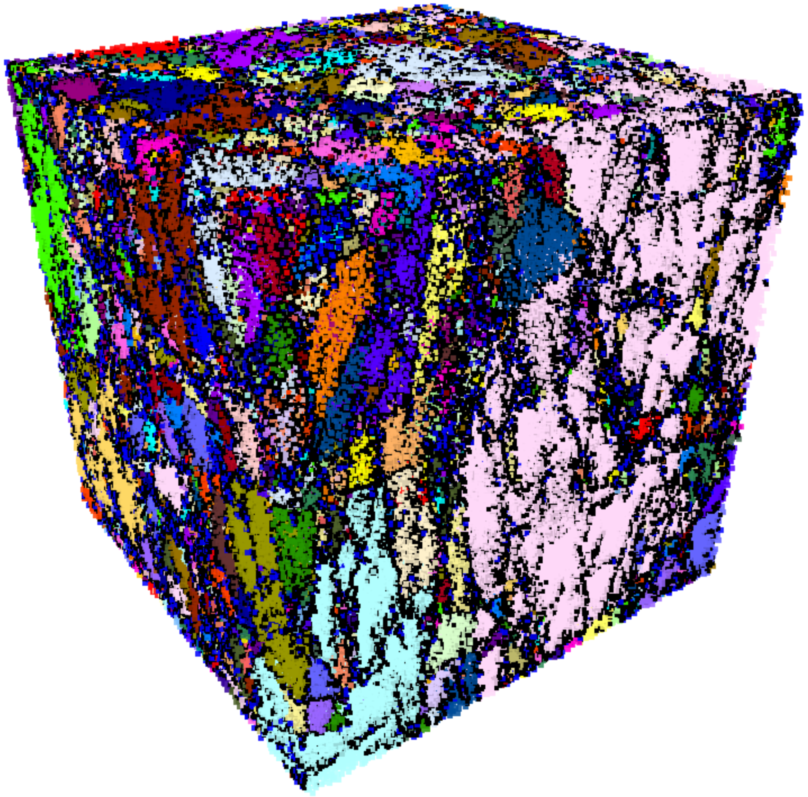
Application of Synthetic Rock Mass modeling for the behavior of fractured reservoirs



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What is Synthetic Rock Mass (SRM) modeling?

- Combination of:

1 – Discrete element method

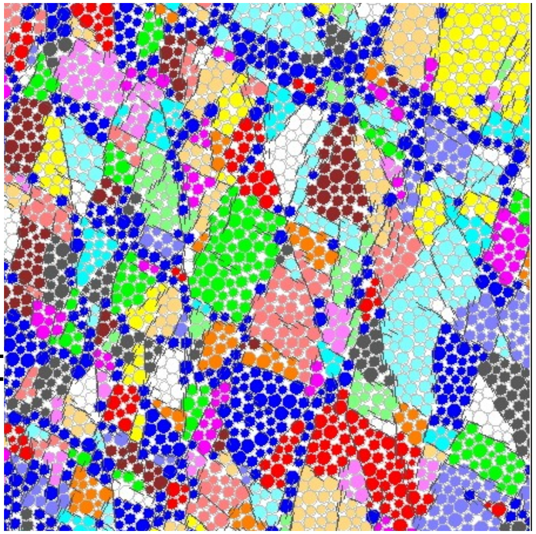
- Numerical tool for the analysis of geomaterials and particulate systems

- Bonded particle systems simulate the geomechanical behaviour of rock (frictional/elastic/brittle)

2 – Smooth joint model

- Representation of rock mass discontinuit

- Allows slip and opening on internal planar surfaces



Discrete element model (DEM)

- Discontinuum mechanics code, simulates the behaviour/deformation of stressed granular assemblies by calculating the displacement of each particle in relation to the forces acting upon it

- Disks (*PFC*^{2D}) or spheres (*PFC*^{3D}) – Cundall and Strack (1979)

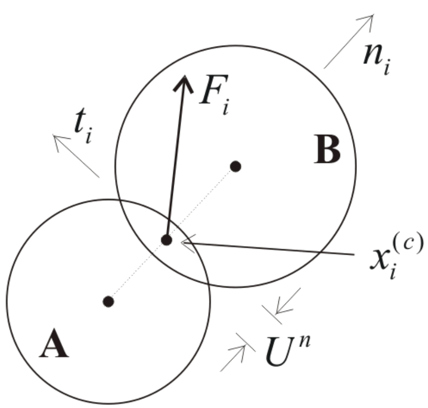
- Explicit time-stepping method, calculation cycle repeated at each time step:

Update particle motion

Newton's 2nd Law (applied to each particle)

Contact Law (applied to each contact)

Update contact forces



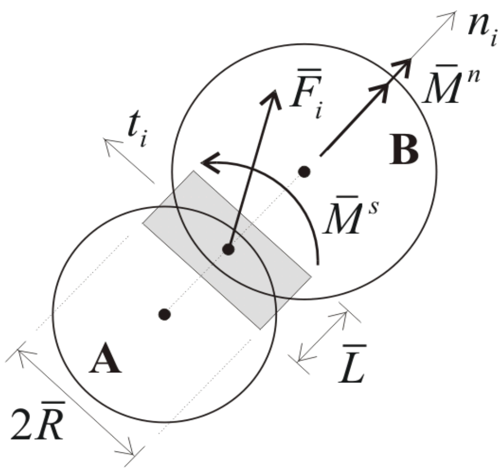
Deformability: $F^n = K^n U^n$

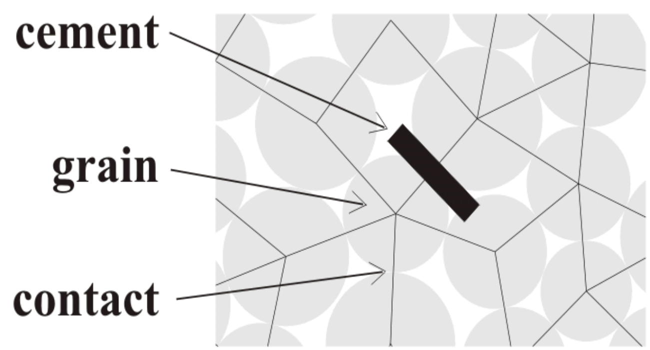
$F^s = -k^s \Delta U^s$

Strength: $F^s \leq \mu F^n$

Discrete element model (DEM)

- ‘Bonds’ may be may be inserted at inter-particle contacts

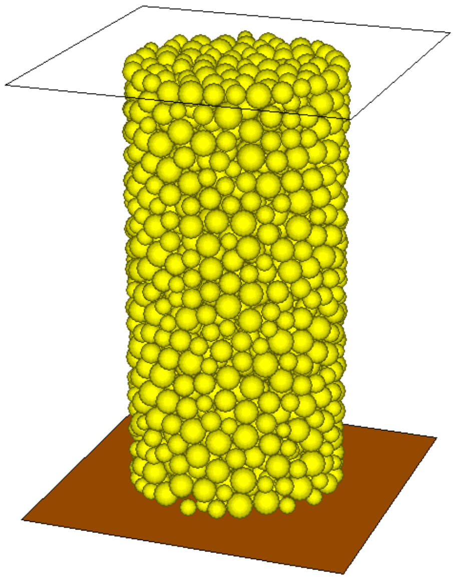




Discrete element model (DEM)

- ‘Bonds’ may be may be inserted at inter-particle contacts

- Bonded assemblies may be subjected to simulated laboratory tests

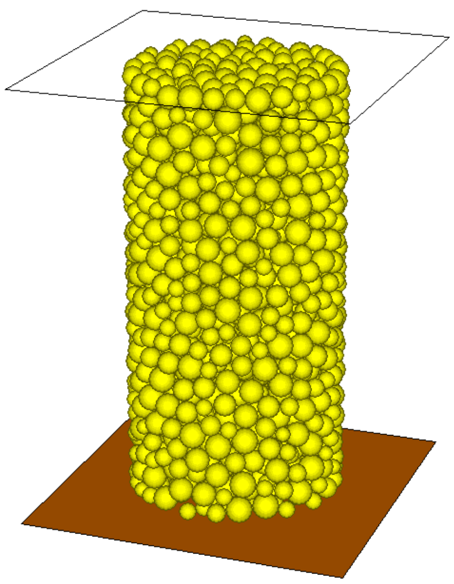


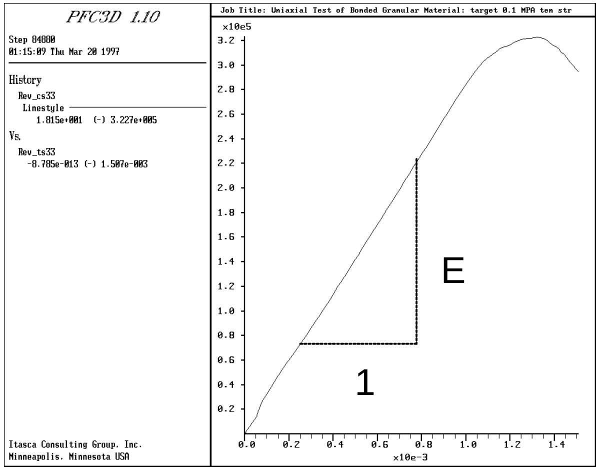
Discrete element model (DEM)

- ‘Bonds’ may be may be inserted at inter-particle contacts

- Bonded assemblies may be subjected to simulated laboratory tests

- Micro-properties of particles/bonds calibrated so that macroscopic response of sample matches known/desired intact rock macro-properties in terms of strength, deformability (elasticity) and brittle behavior

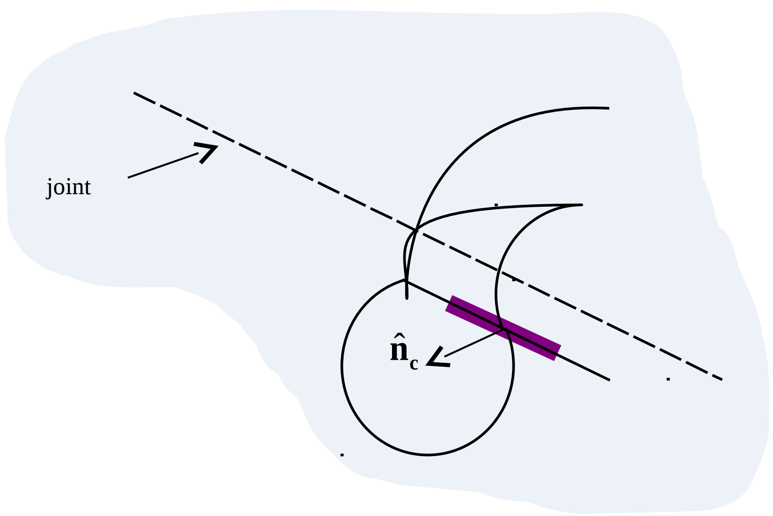


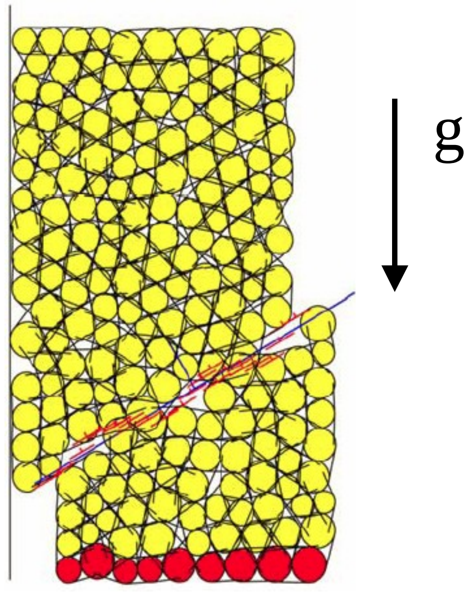


Smooth joint contact model

- Representation of rock mass discontinuities through simulation of a smooth interface

- Particle pairs joined by a smooth joint contact where the particles may overlap and slide past one another rather than being forced to move around one another





Smooth joint contact model

- Discrete fracture network (DFN)

- To understand/quantify fracture characteristics:

    - Orientation, aperture width, length, spatial distribution, connectivity, etc.

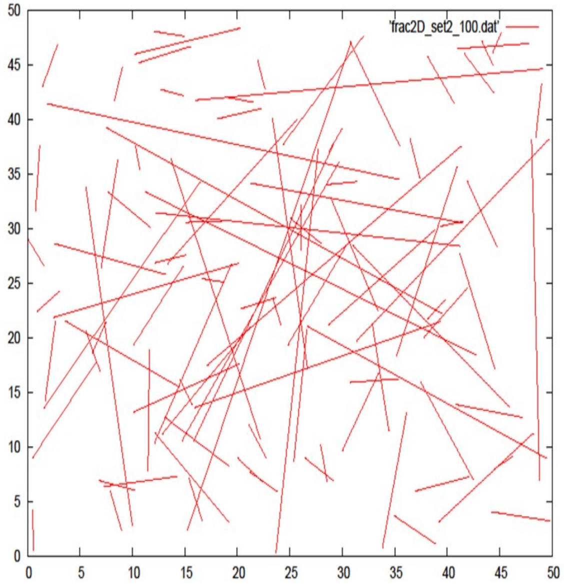
- Developed through input from:

    - Seismic

    - Borehole analysis (e.g., core, televi

    - Outcrop analogues

    -Theoretical/statistical models

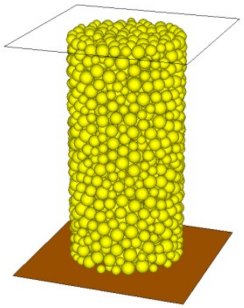


- 50 m

- 100 fractures

- Power law fracture length distribution

Creation of SRM



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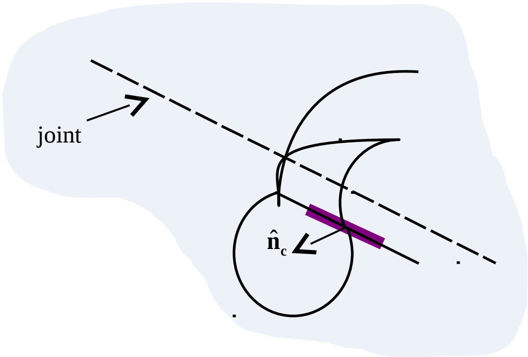

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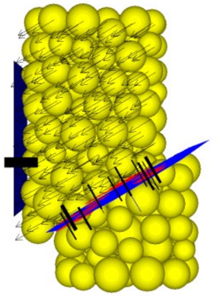

Intact rock representation

Smooth Joint model

Jointed rock

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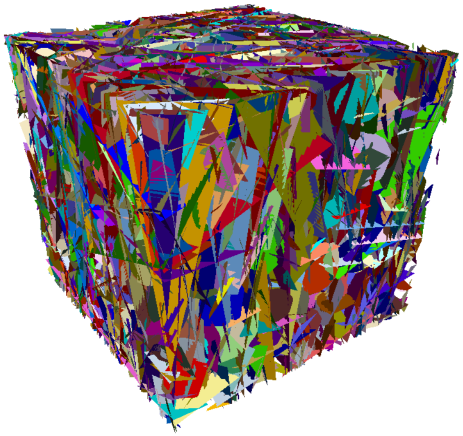

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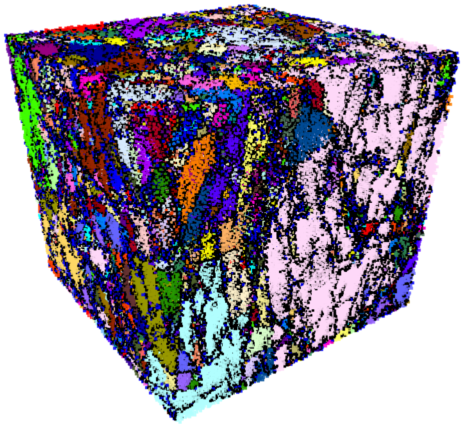


DFN

SRM

'Numerical rock mass' block which honors both the properties of the intact rock and fracture characteristics and distribution

Objectives of study

1 – Direct

- Explore the use (and limitations) of the SRM approach for modeling the geomechanical behavior of fractured rock masses/reservoirs

- Comparison with analytical/continuum solutions

- Limited scale (≤100 m blocks in 3D)

2 – Indirect

- Determination of the macroscopic properties of relatively small-scale (m) SRM samples for use numerical simulations more suitable to reservoir-scale

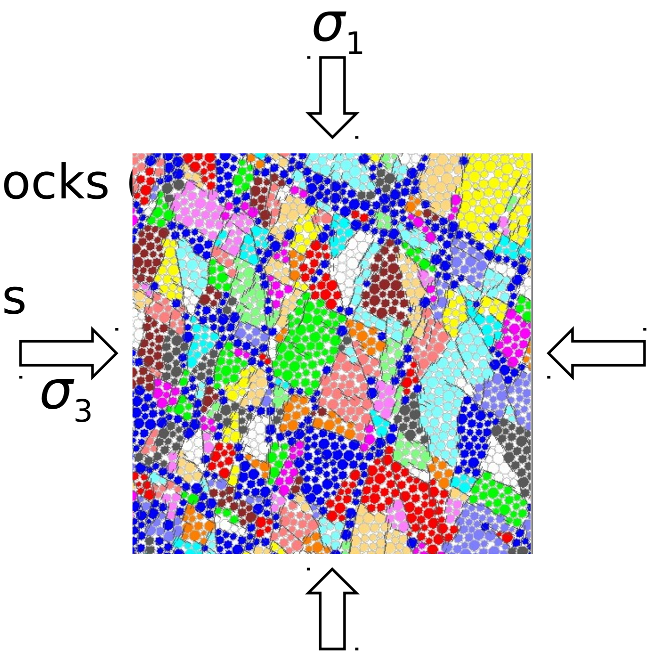
- *MDEM* (hybrid continuum/discontinuum)

- Developed under *ROSE* Project by H. Alassi

Progression of study

Direct: 2D → 3D → Geologic model

- Consideration of the behaviour stressed blocks (



- Range of intact rock and joint properties

- DFNs generated via statistical models

- **Static** scenarios:

- Variation of stress with depth
- Variation of stress ratios

• What is the state of stress on the fractures?
• Is there fracture propagation or new fracture formation?
• How does this vary with *in situ* stress state?
• How do the results compare with analytical solutions?
• How do the results compare with continuum numerical solutions?
• What is the seismic response of the stressed blocks and how does this vary?

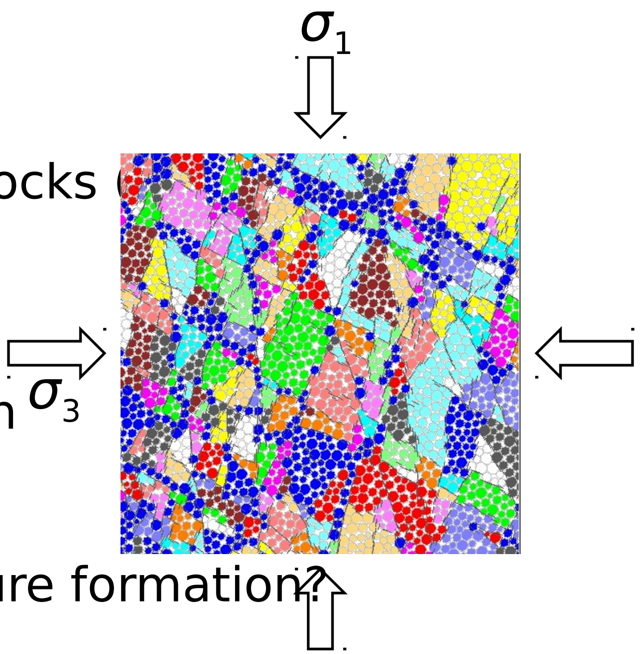
Progression of study

Direct: 2D → 3D → Geologic model

- Consideration of the behaviour stressed blocks (

  - **Dynamic** scenarios:

    - Stress increase due to depletion



- How does fracture stress state vary?
- Is there fracture propagation or new fracture formation?
- Dependency on *in situ* stress state?
- How do the results compare with analytical solutions?
- Associated microseismicity? Microseismicity patterns?
- What are the implications for permeability anisotropy?

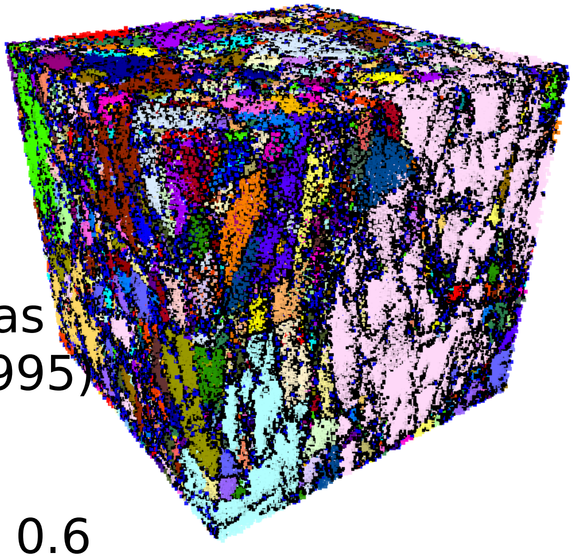
  - Fracture aperture tracking as a function of stress
  - Flow through a network of connected ‘pipes’ along fracture

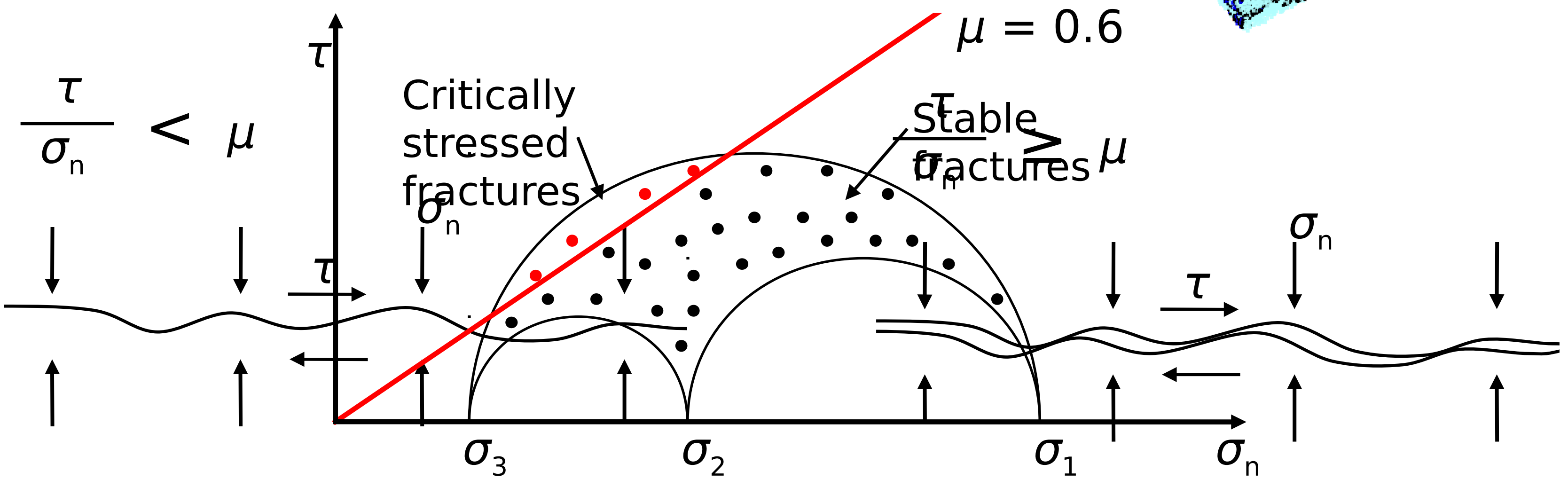
    - Injection scenarios, also possible in *MDEM*

Progression of study

Direct: 2D → 3D → Geologic model

- Addition of intermediate stress
- Critically stressed fracture analysis
  - Critically stressed fractures recognized as crucial fluid pathways by Barton et al. (1995)

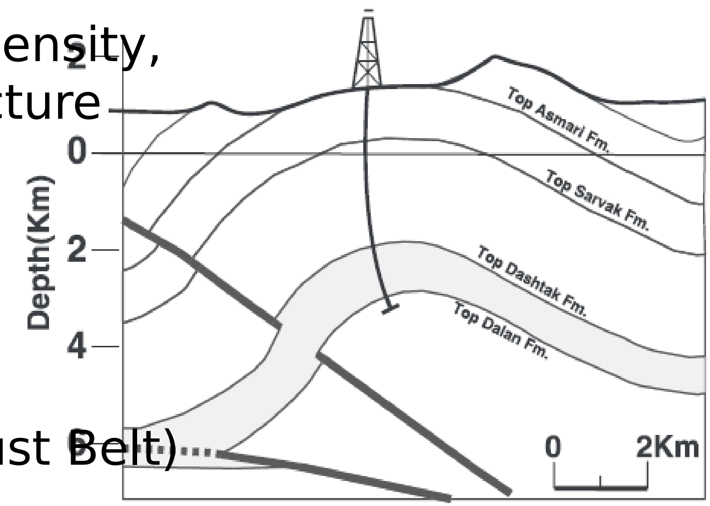




Progression of study

Direct: 2D → 3D → Geologic model

- Variation in fracture orientation, density, connectivity within a geologic structure

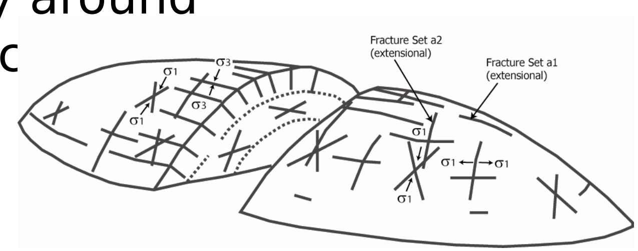


Sherkati and Letouzey (2004)

- Fractured carbonate anticline

- Middle East (Zagros Fold and Thrust Belt)

- Fracture patterns vary systematically around the structure as a result of folding proc



Cosgrove and Ameen (2000)

Progression of study

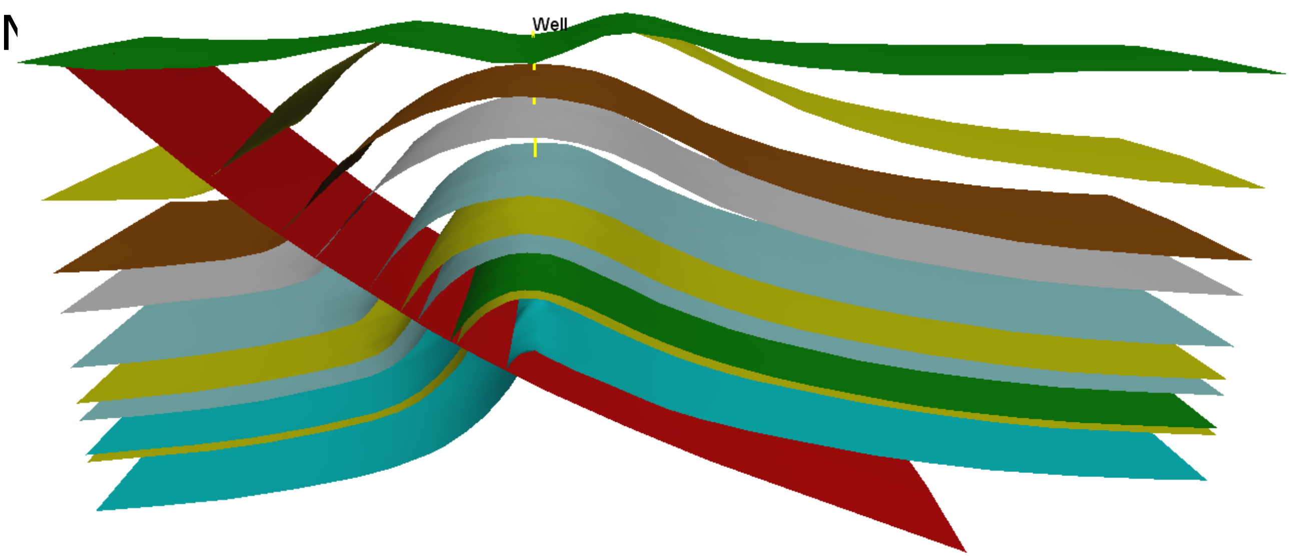
Direct: 2D → 3D → Geologic model

- Geologic reconstruction in *MOVE* software

- Kinematic reconstruction of geologic structures based on geologic principles

- Allows for consideration strain evolution in structure through time

- DFN



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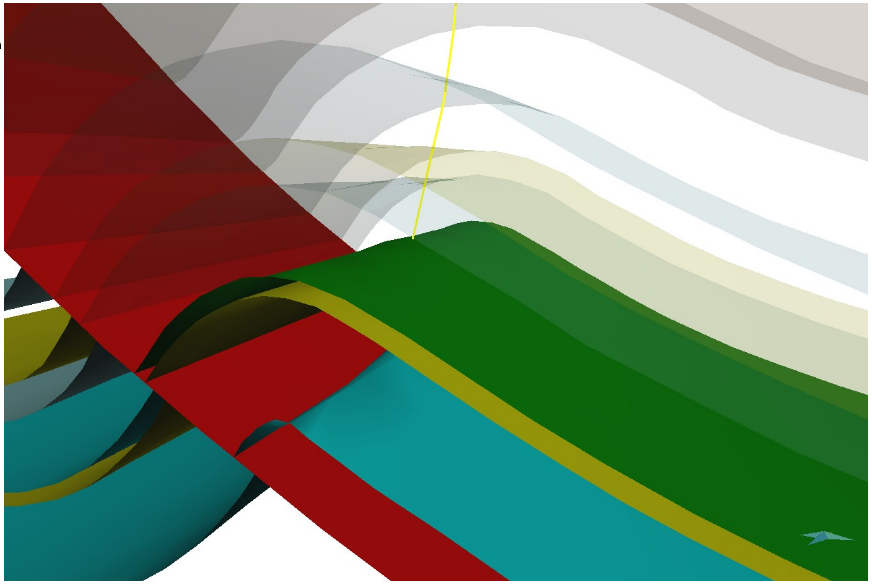

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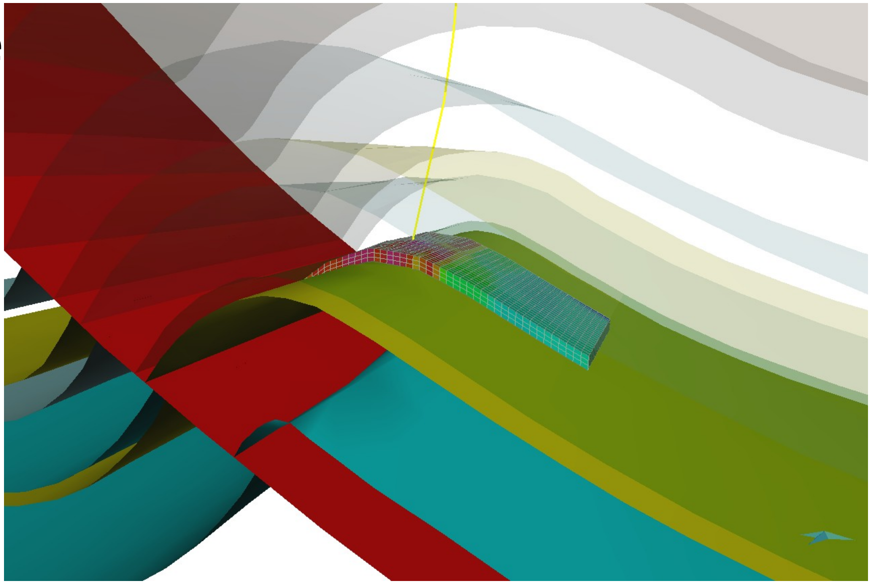

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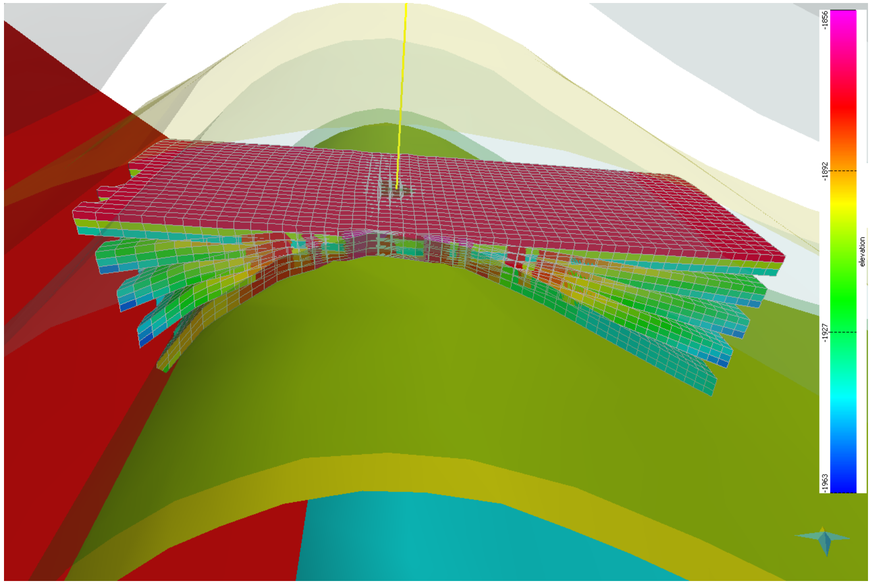

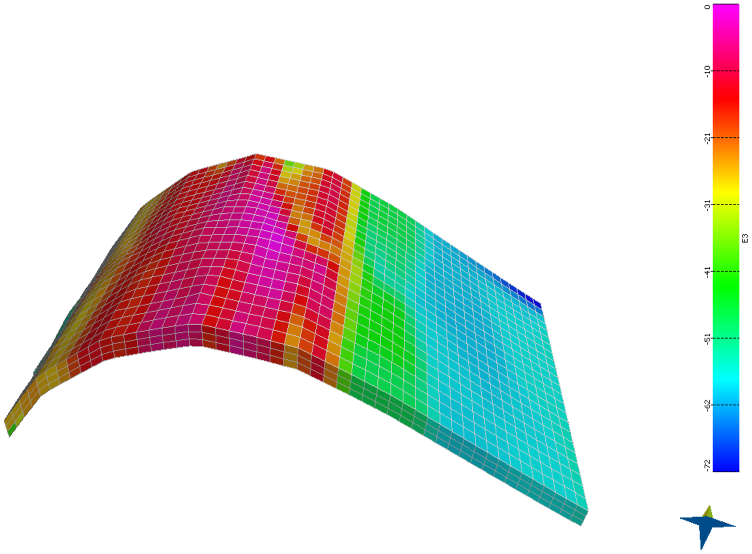

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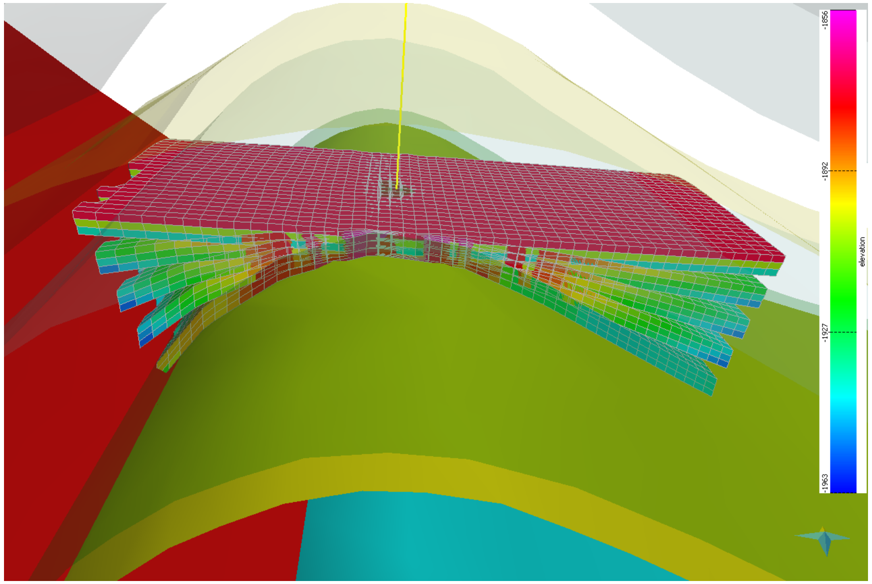

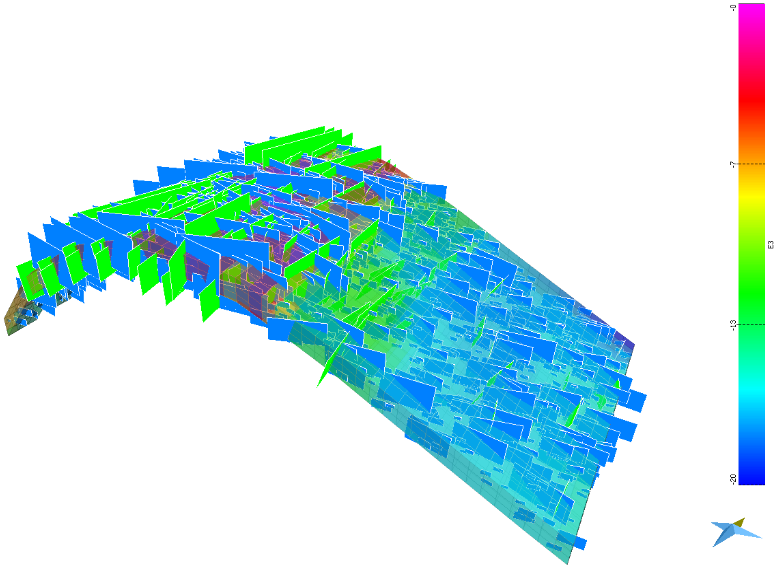

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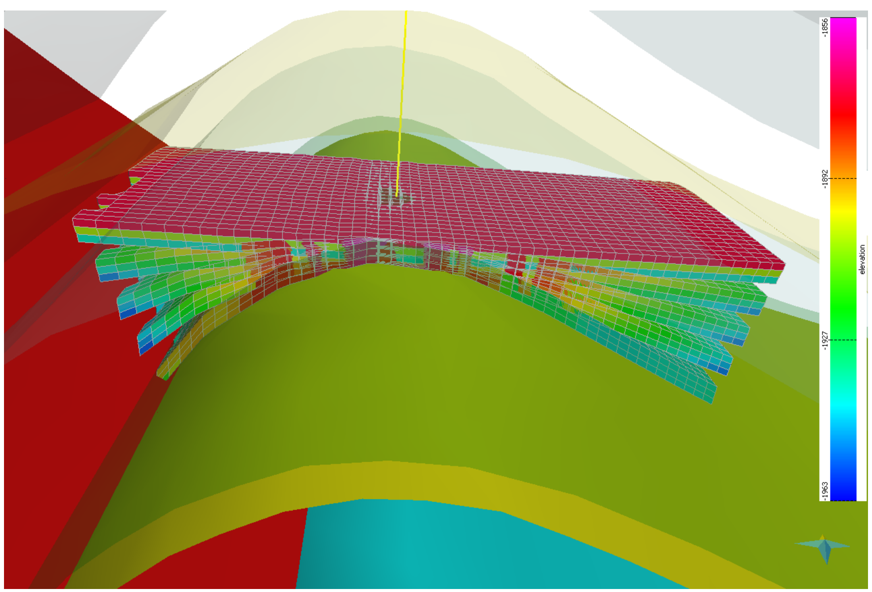
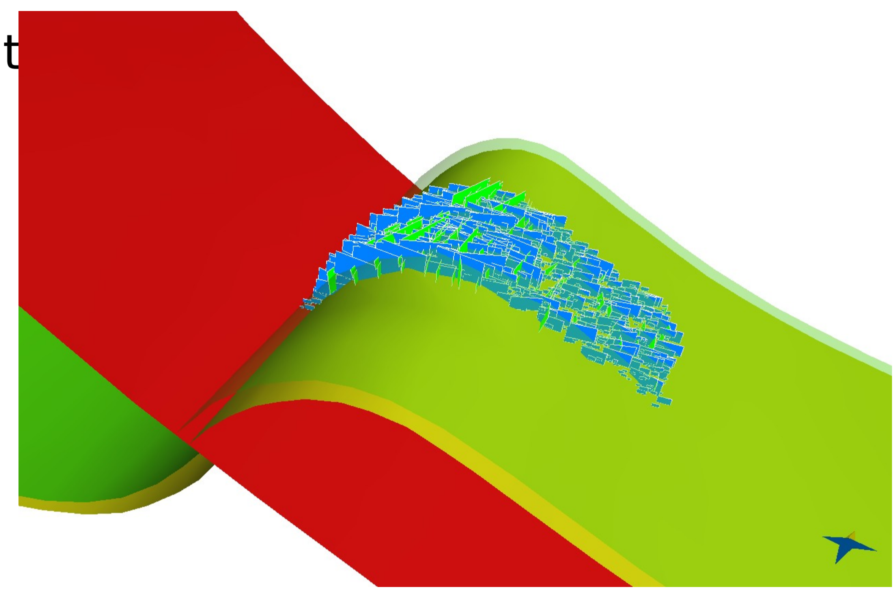




Progression of study

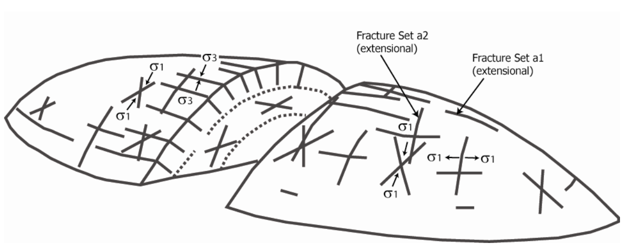
Direct: 2D → 3D → Geologic model

- Spatially variable DFN, characteristics based on structural evolution (strain history)

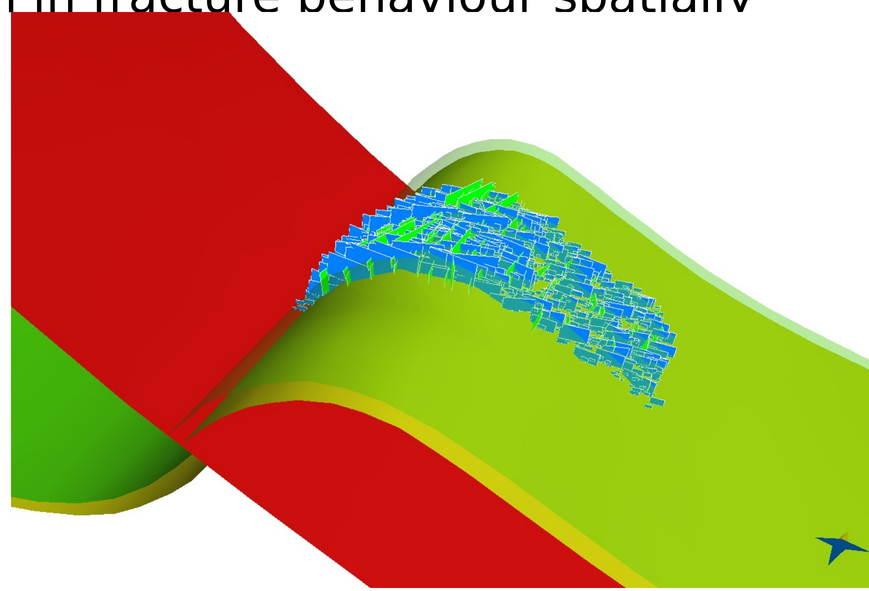
- Sections of DFN can be used to construct SRM models

- SRM subjected to stress path observed in continuum simulations

- Determination of the variation in fracture behaviour spatially



Cosgrove and Ameen (2000)

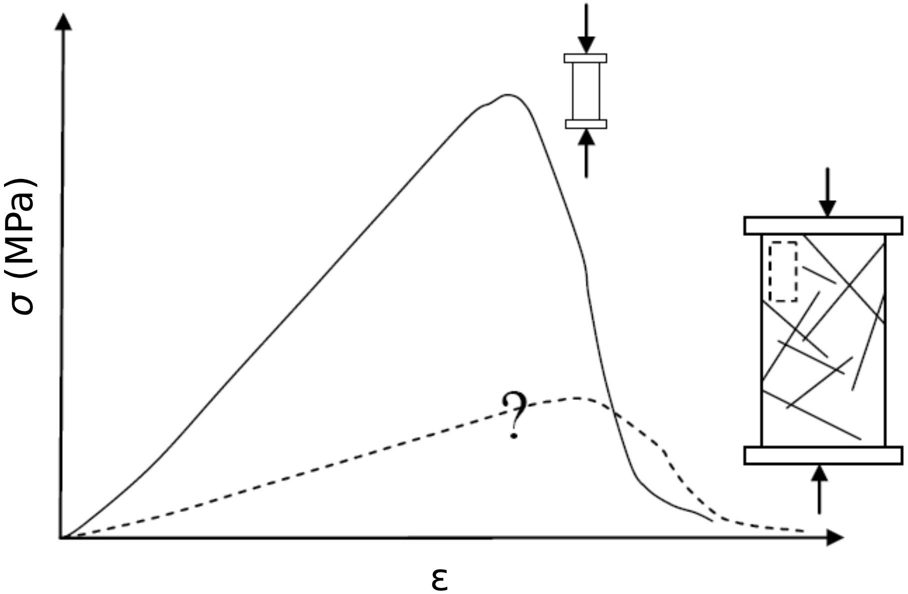


Progression of study

Indirect:

- Use of SRM samples to determine rock <u>mass</u> properties

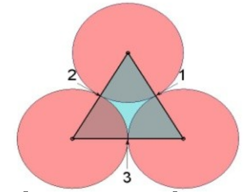
- Behavior/properties determined can be used as input for geomechanical simulators more suitable to large (i.e. km) scale



Progression of study

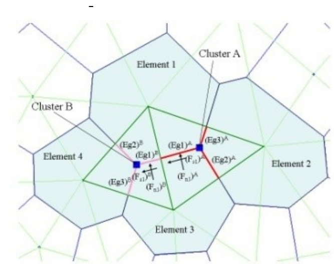
Indirect:

- *MDEM* (<u>M</u>odified <u>D</u>iscrete <u>E</u>lement <u>M</u>ethod)

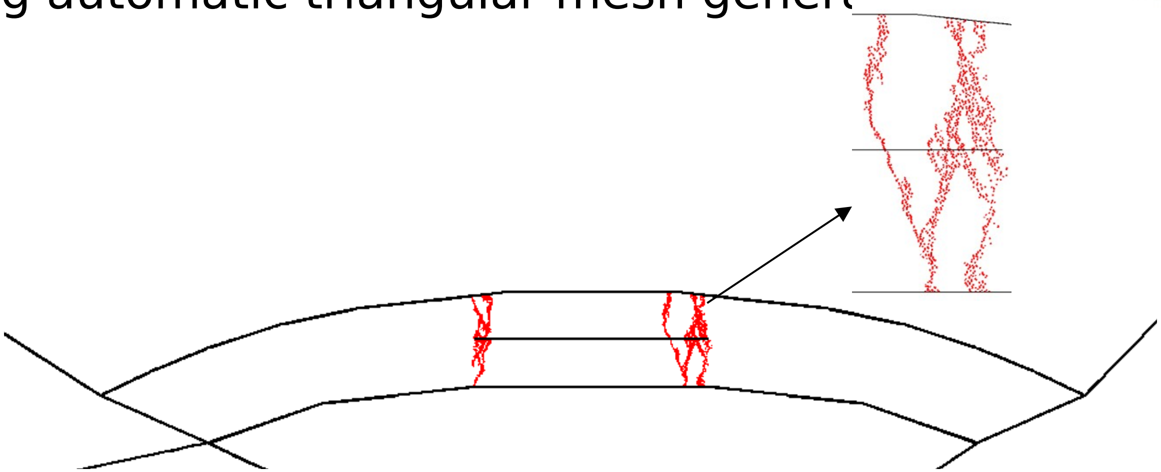


  - Works with particle clusters rather than individual elements

  - Behaves as a continuum before failure and a disc
afterwards



  - Straightforward to build km-scale geomechanical
using automatic triangular mesh generation



Fracture development during fluid injection

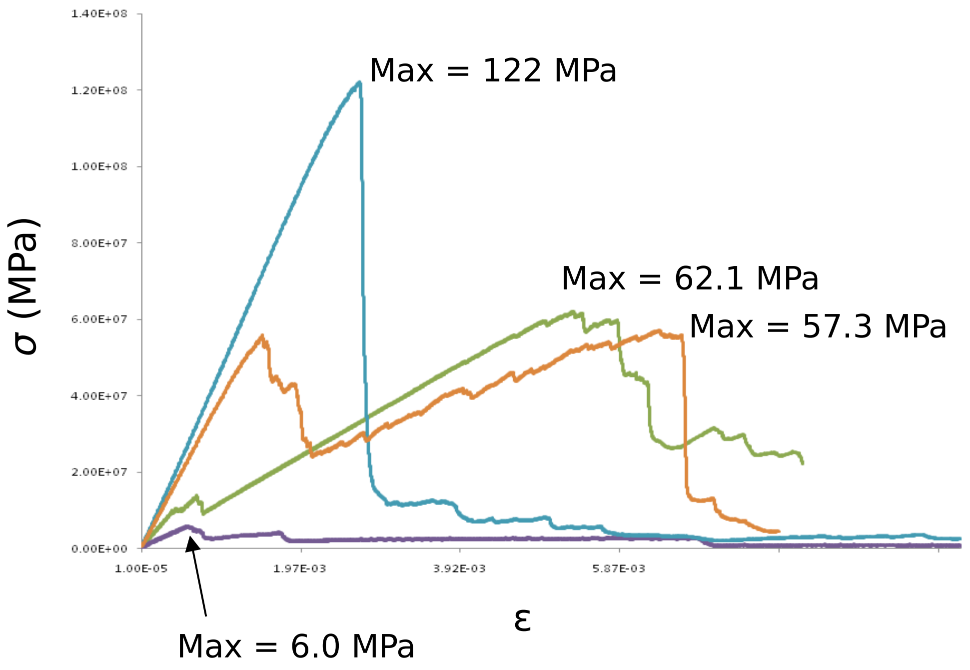
Progression of study

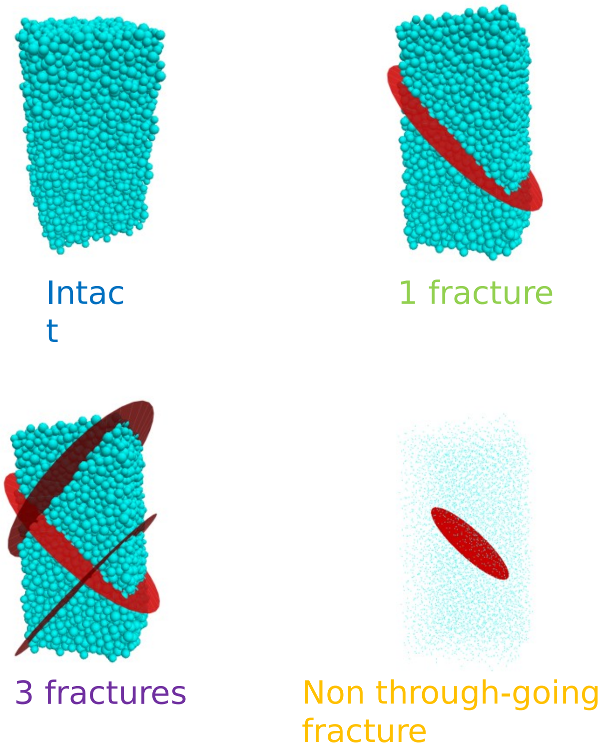
Indirect:

- Uniaxial test on a 2x2x4 m block of 'carbonate'

- Intact elastic properties: E = 50 GPa, v = 0.25

- 45° fracture(s), μ = 0.6





Current progress

Direct study, 2D:

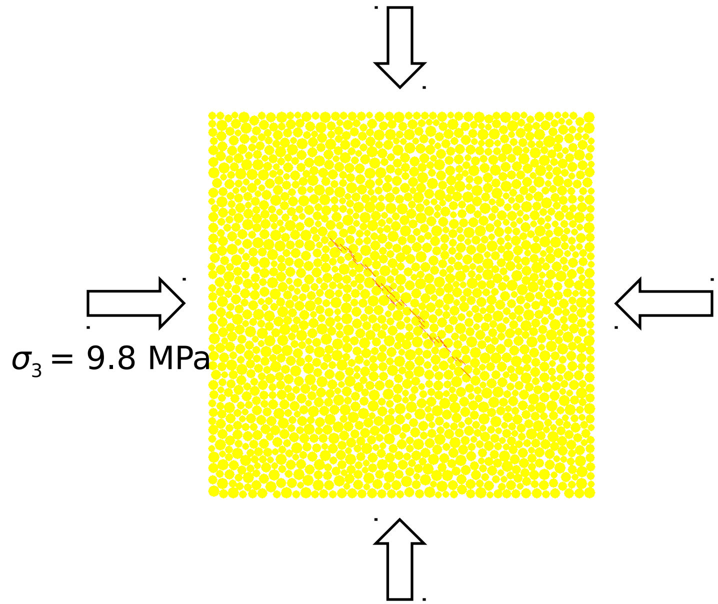
- Comparing fracture stress condition at depth with analytical solutions

- Effective stress scenario at 2000 m depth (ρ = 2000 g/cm^3)

- 10x10 m block, 1834 particles, mean 0.25 m diameter

- Intact rock mass properties:
    - UCS = 100 MPa
    - E = 50 GPa
    - v = 0.25

- 4 m, 45° fracture
    - μ = 0.6



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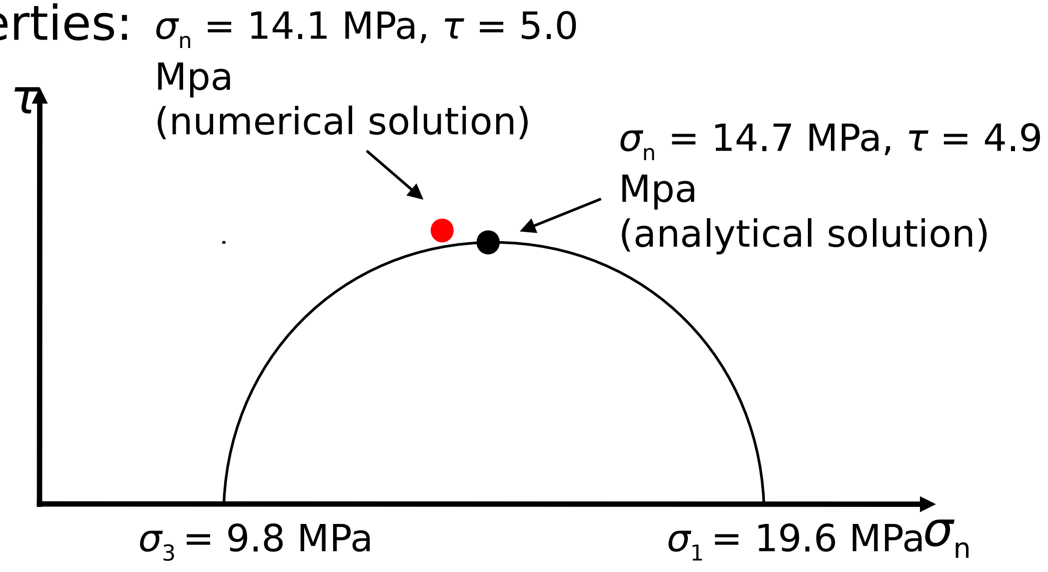

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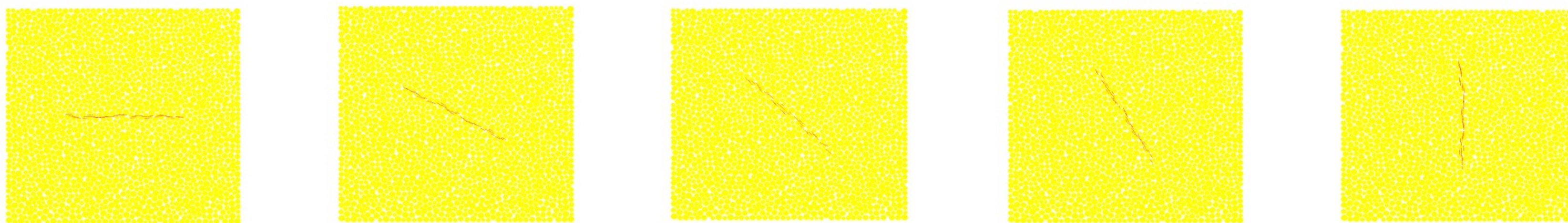
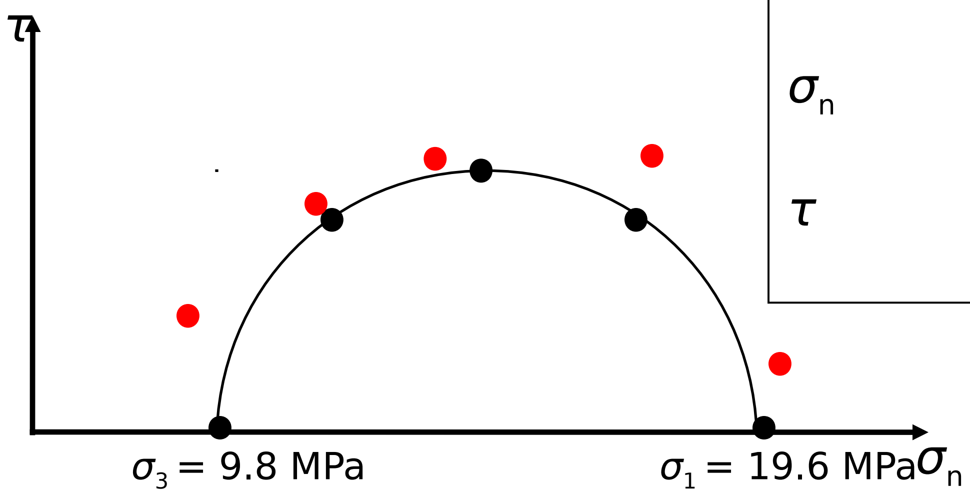
Direct study, 2D:



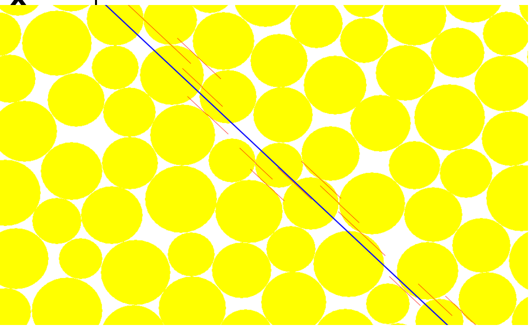
θ = 0° θ = 30° θ = 45° θ = 60° θ = 90°



Difference (mean)

σ_n - 1.1x

τ + 1.



Next steps

Direct study, 2D:

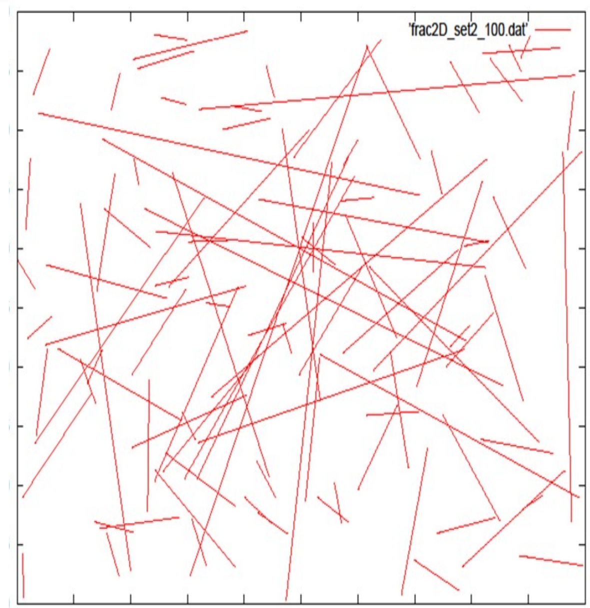
- Introduction of DFN

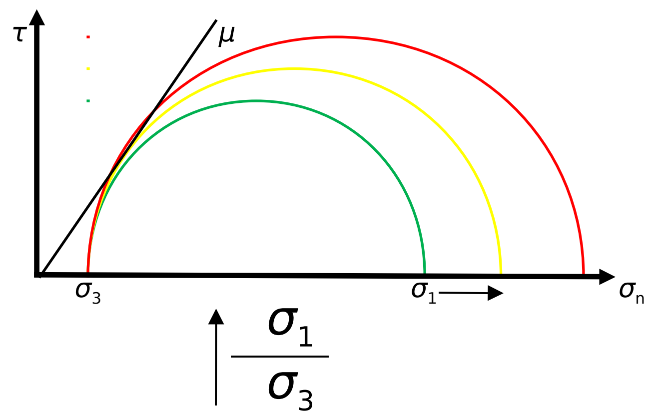
- Variation of stress state:

    - Fracture propagation?

    - New fracture development?

    - Etc.?





Thank you

References

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