Simulating Spalling with a Flat-Jointed Material

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Summary Image (real system)

Assess ability of 3D flat-jointed material
to model spall initiation in intact Äspö diorite

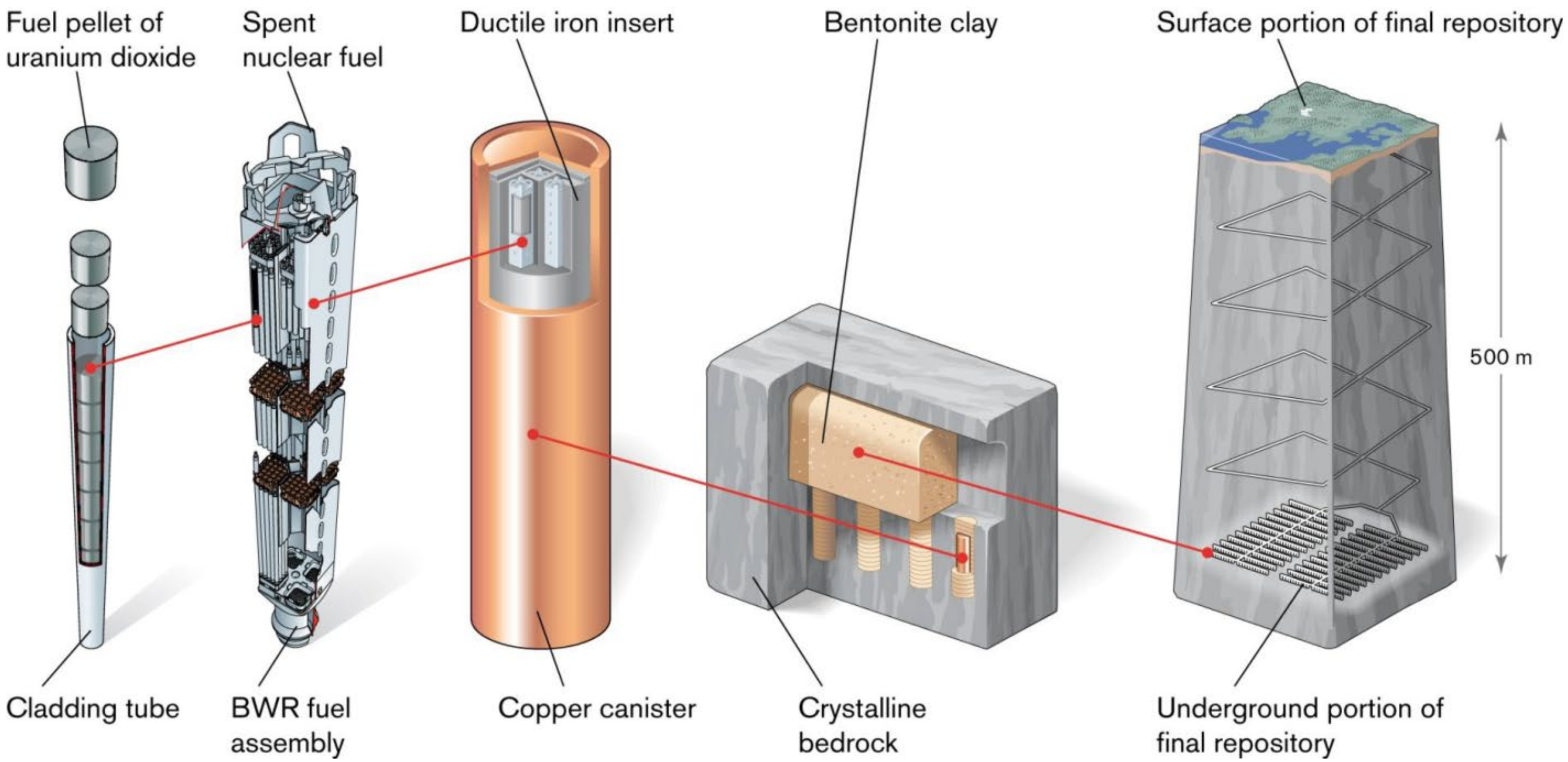
Äspö Diorite

Äspö Pillar Stability Experiment

Nuclear Spent Fuel (long-term storage)

The Goal: safe geological disposal

- Waste canisters are to be placed in deposition holes



Nuclear Spent Fuel (long-term storage)

The Goal: safe geological disposal

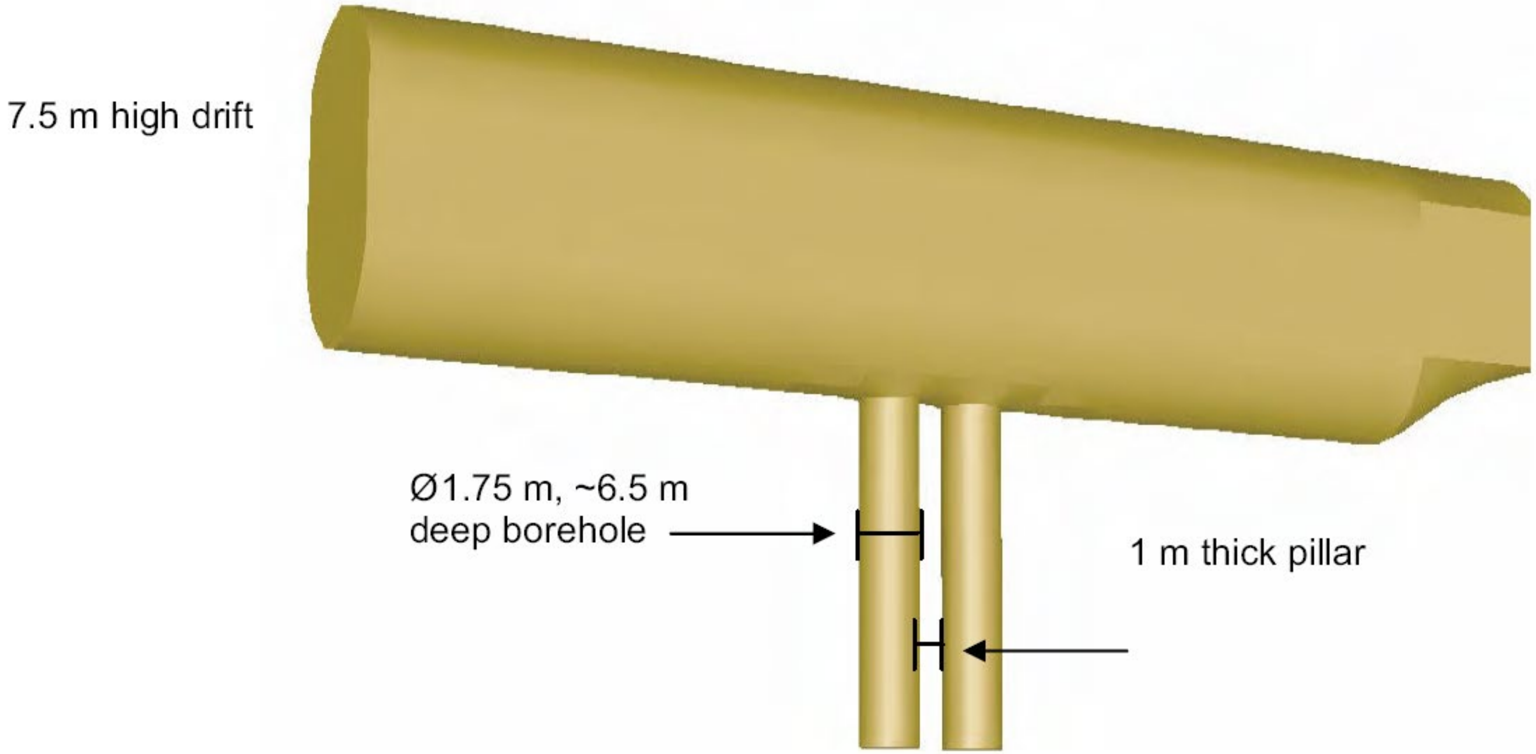
- Waste canisters are to be placed in deposition holes
- Thermal loading ➔ increases rock stresses ➔ spalling?
- Spalled region ➔ increase fluid flow ➔ negative impact on final safety assessment

Nuclear Spent Fuel (long-term storage)

- Modeling:
  - Desire enhanced understanding of spalling
  - Mimic rock microstructure ➔ capture relevant physical processes
  - Match laboratory response of Äspö diorite
    - Direct tension & compression tests
    - Near peak load in UCS tests, axial splits form (similar to spalls)

Spalling Phenomenon (experiment)

- Äspö Pillar Stability Experiment

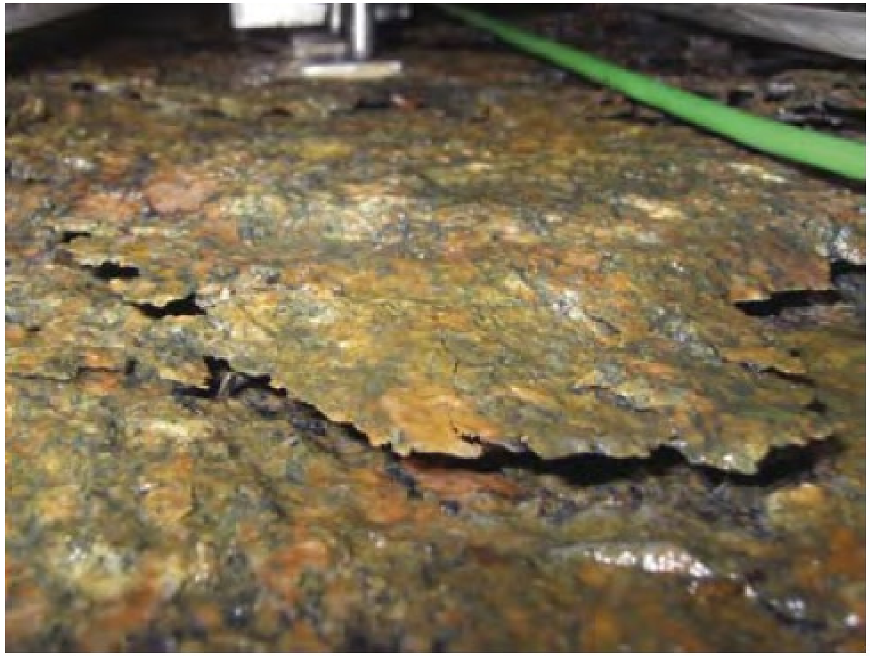


Drill two boreholes to create a pillar, then heat the pillar.

Spalling Phenomenon (experiment)

- Äspö Pillar Stability Experiment

Initial spalling during drilling

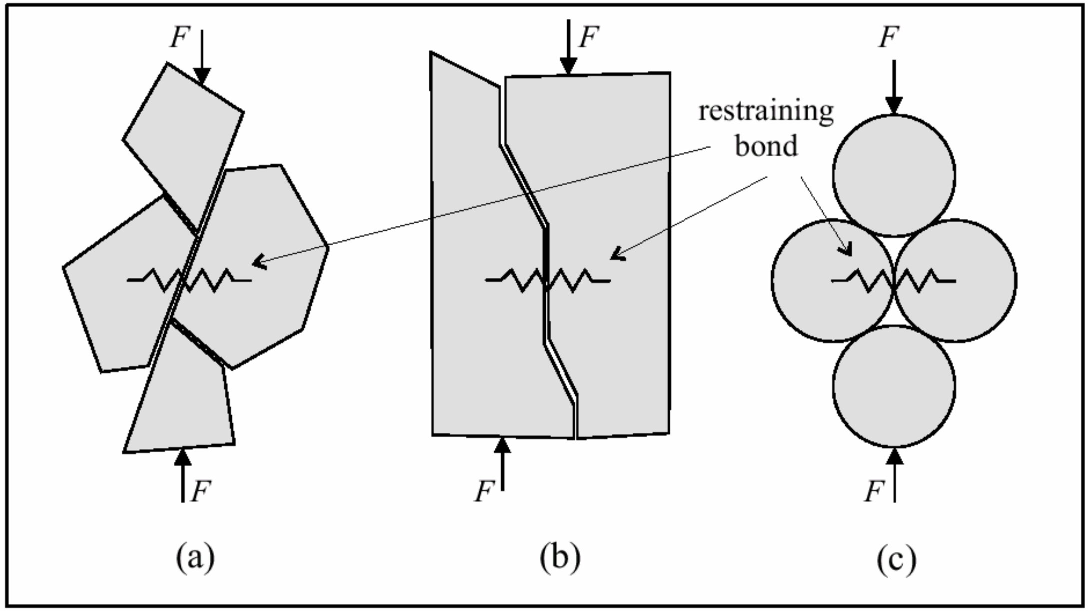


Close-up of pillar wall

thin slabs, buckled

Spalling Phenomenon (guiding hypothesis)

- Spalling occurs because of a heterogeneous microstructure
  - Macroscopic loading ➔ micro-tensions ➔ microcracks aligned with compression direction



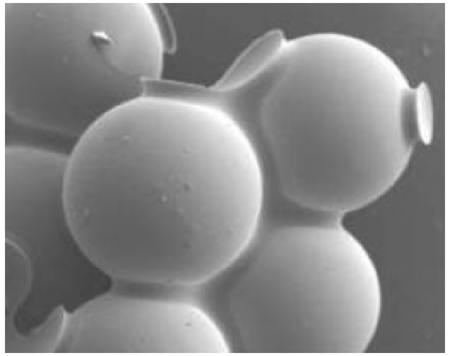
Physical mechanisms for compression-induced tensile cracking

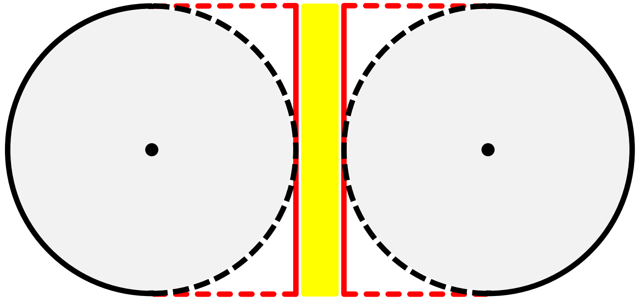
Spalling Phenomenon (guiding hypothesis)

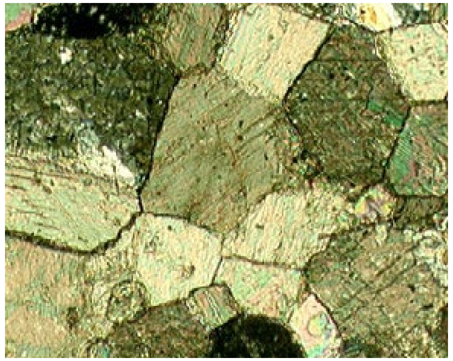
- Spalling occurs because of a heterogeneous microstructure
  - Macroscopic loading → micro-tensions → microcracks aligned with compression direction
  - This process is very sensitive to confinement
    - increased confinement → reduced cracking
  - Near a free surface
    - Tangential stress produces spalling
    - Confinement increases with depth, spalling stops

Flat-jointed material (Differs from parallel bond)

intact parallel bond

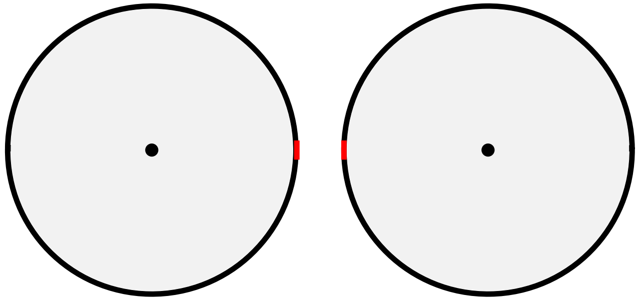






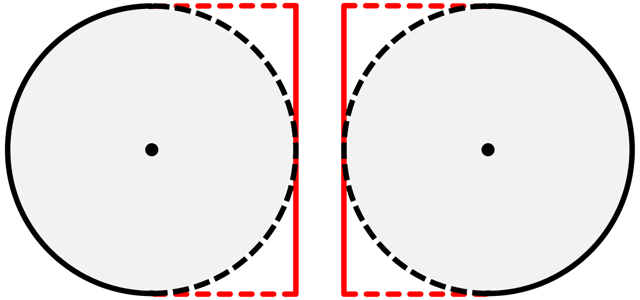
bonded finite-length interface

broken parallel bond



frictional zero-length interface

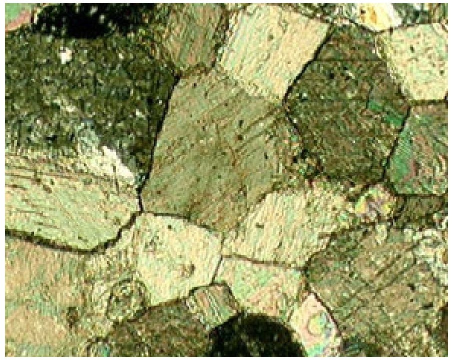
fully broken flat joint

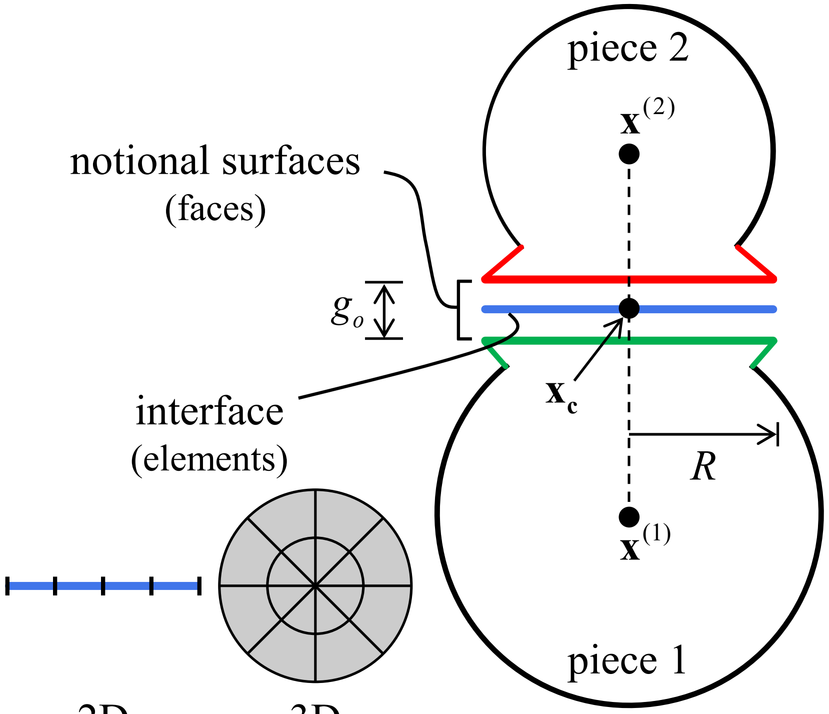


frictional finite-length interface

Flat-jointed material (microstructure)

Marble with angular, interlocked grains



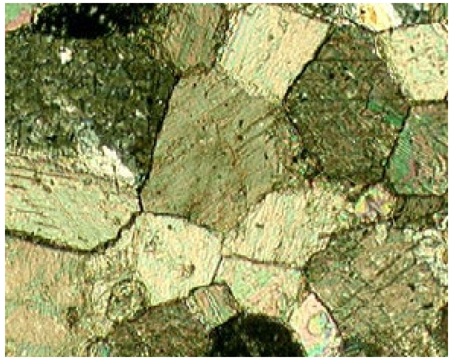


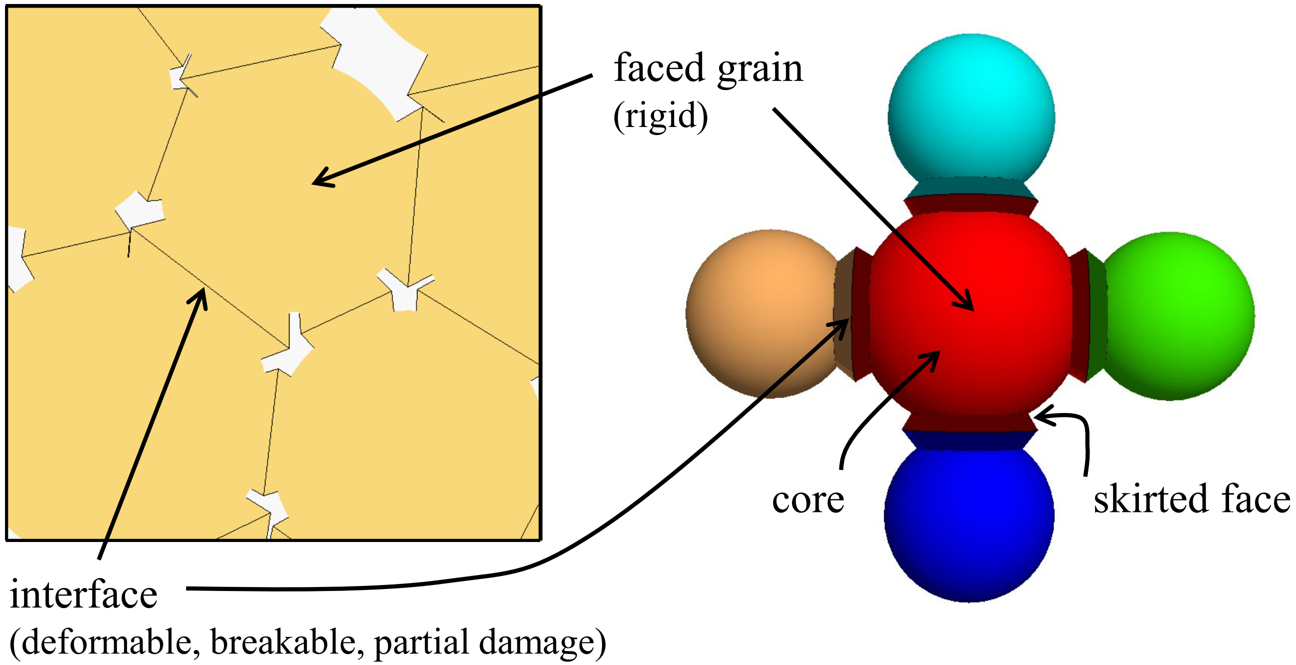
flat-joint contact

Each interface is discretized into elements that may be initially bonded, after breakage they are frictional.

Flat-jointed material (microstructure)

Marble with angular,
interlocked grains

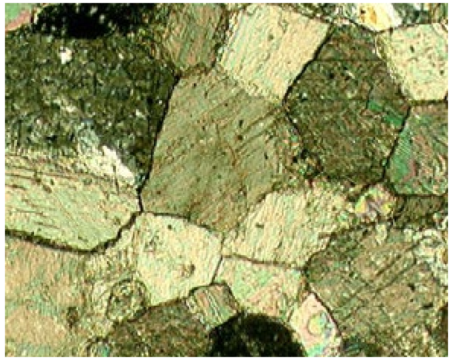




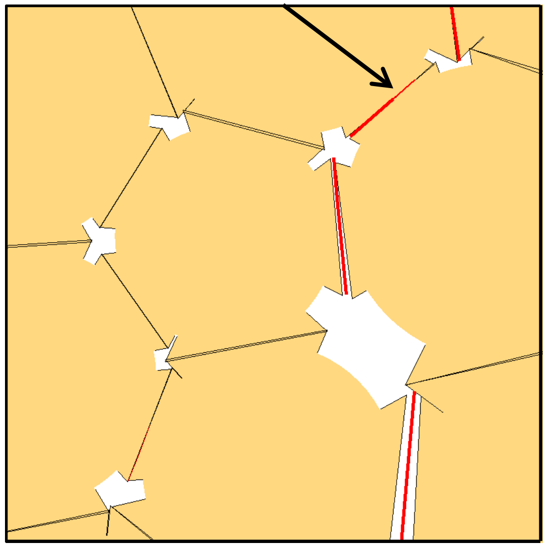
flat-jointed material
consists of faced grains

Flat-jointed material (microstructure)

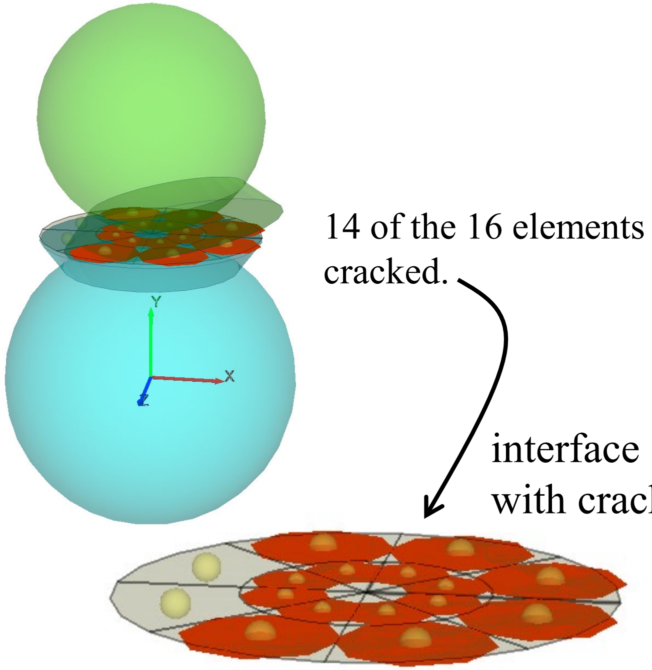
Marble with angular, interlocked grains



Bending failure with 3 of the 4 elements cracked.



Crack thickness is proportional to gap.



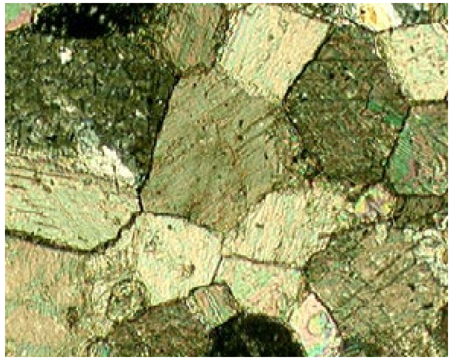
14 of the 16 elements cracked.

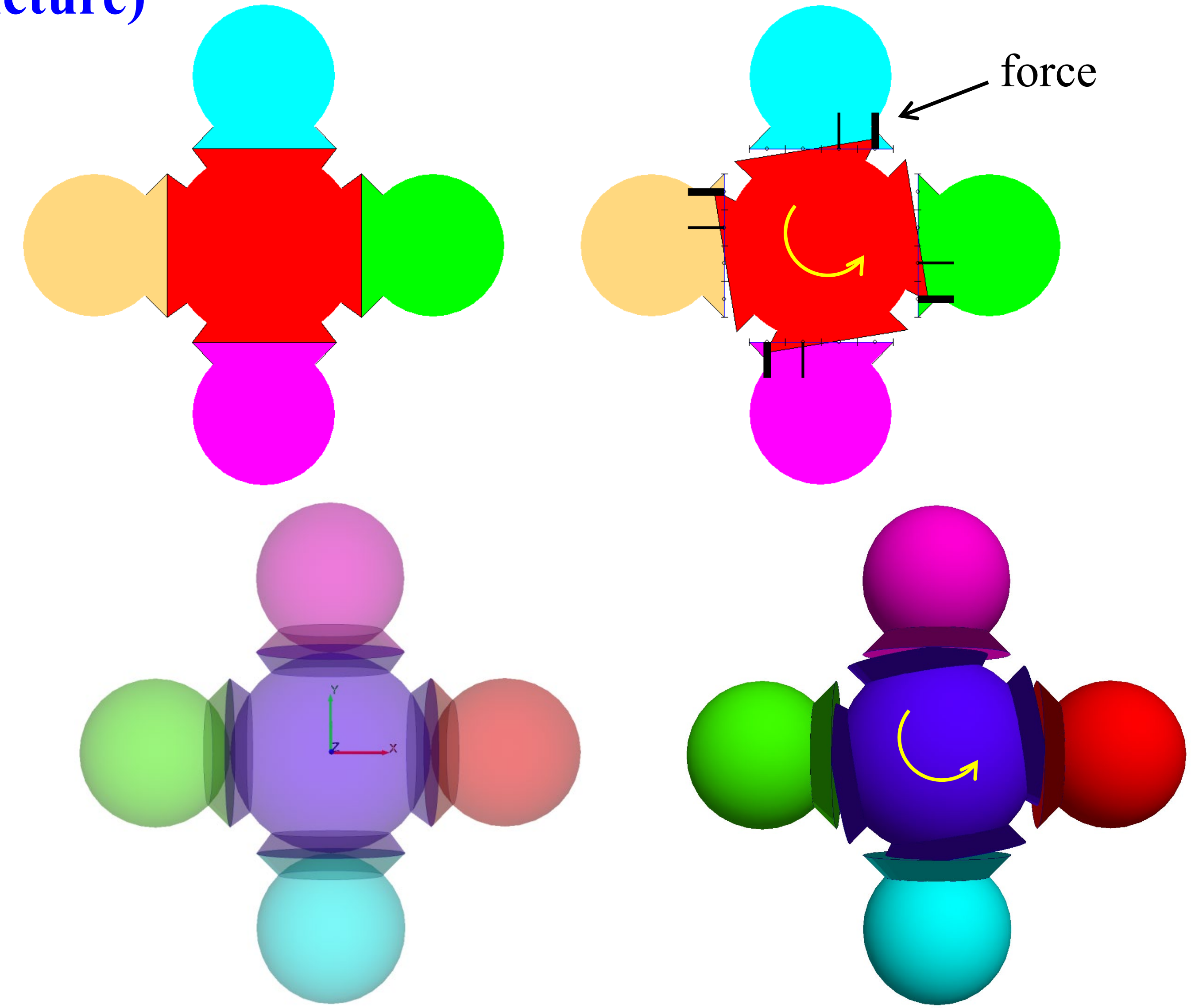
interface with cracks

The interface can sustain partial damage.

Flat-jointed material (microstructure)

Marble with angular, interlocked grains

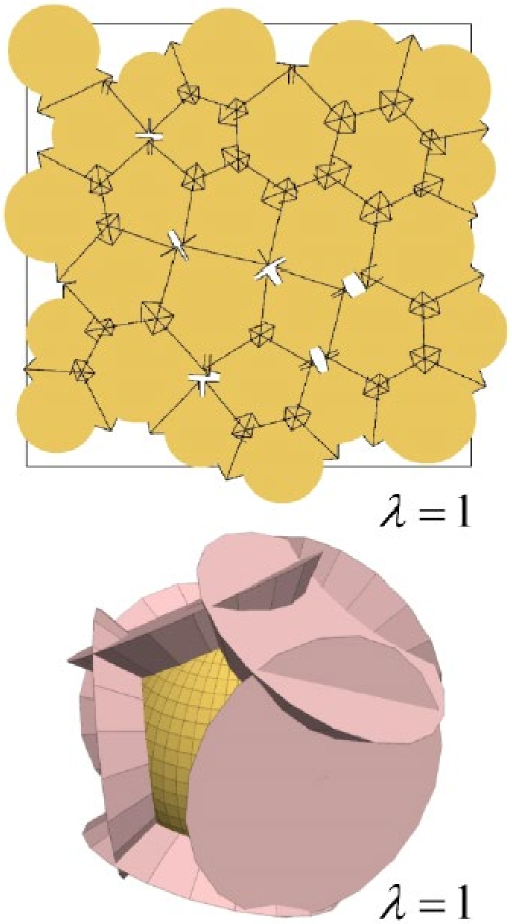




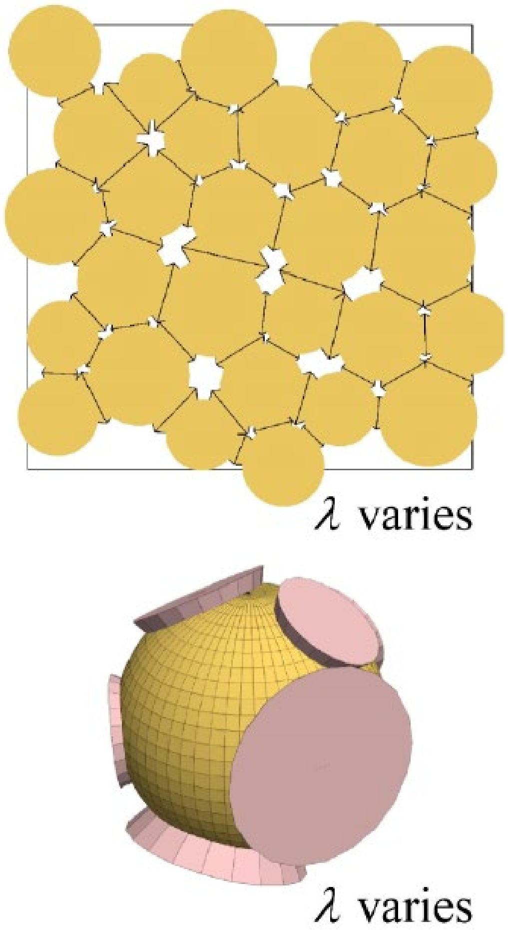
Even a fully broken interface continues to resist relative rotation.

Microstructural Validity (valid & invalid)

FJ microstructure is valid if and only if faces of each grain can be connected to grain center with no overlap.



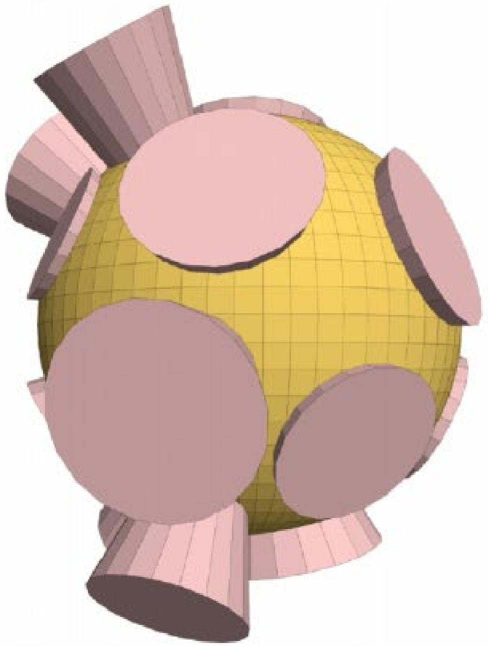
invalid



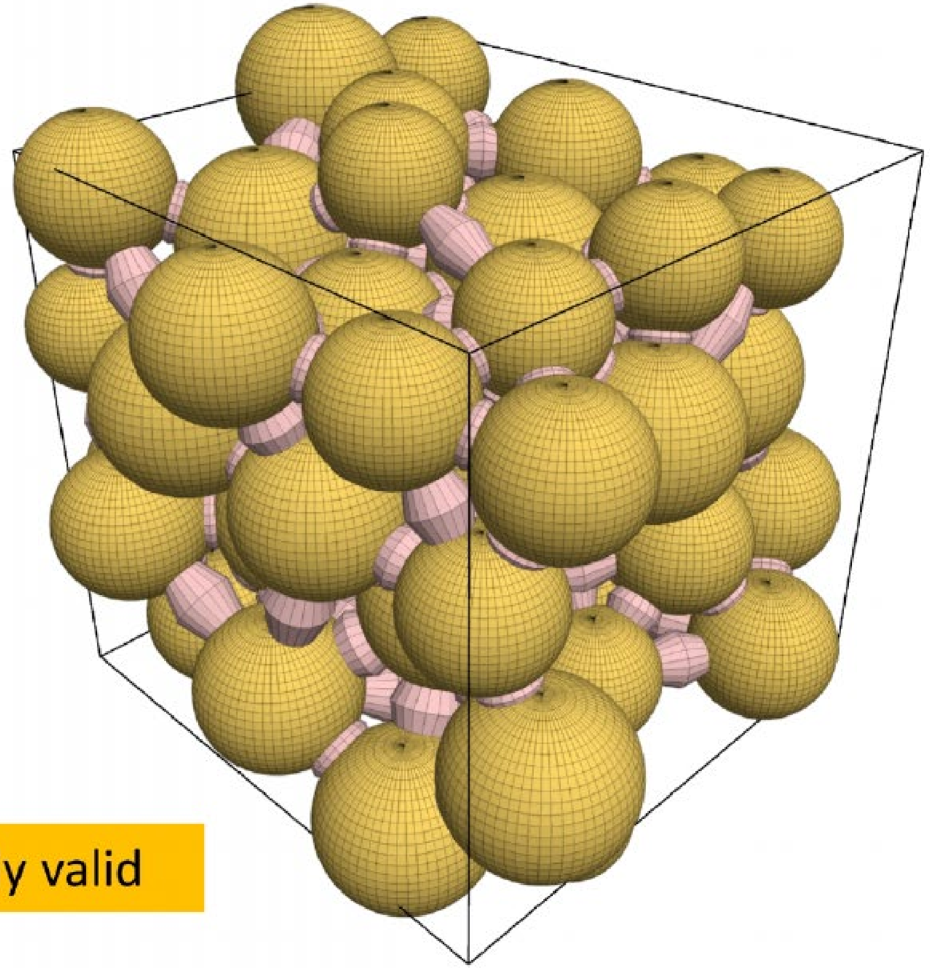
valid

Microstructures (3D, valid)

Unrealistic: (1) excessively long cement bridges, (2) microproperties 3.5 times larger than corresponding macroproperties



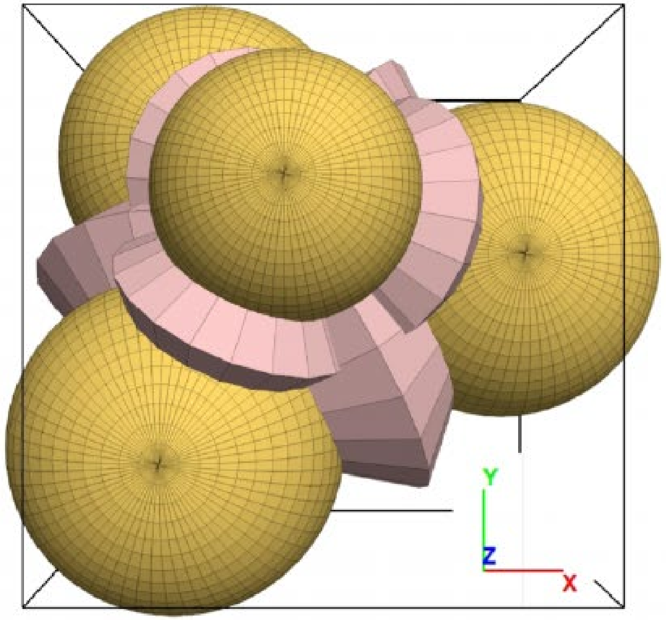
cube, s = 18 mm

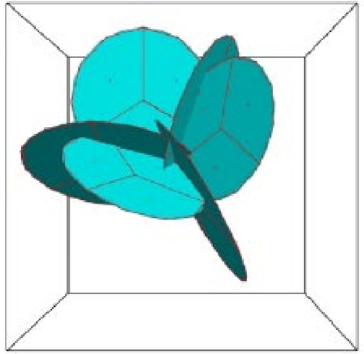


Microstructurally valid

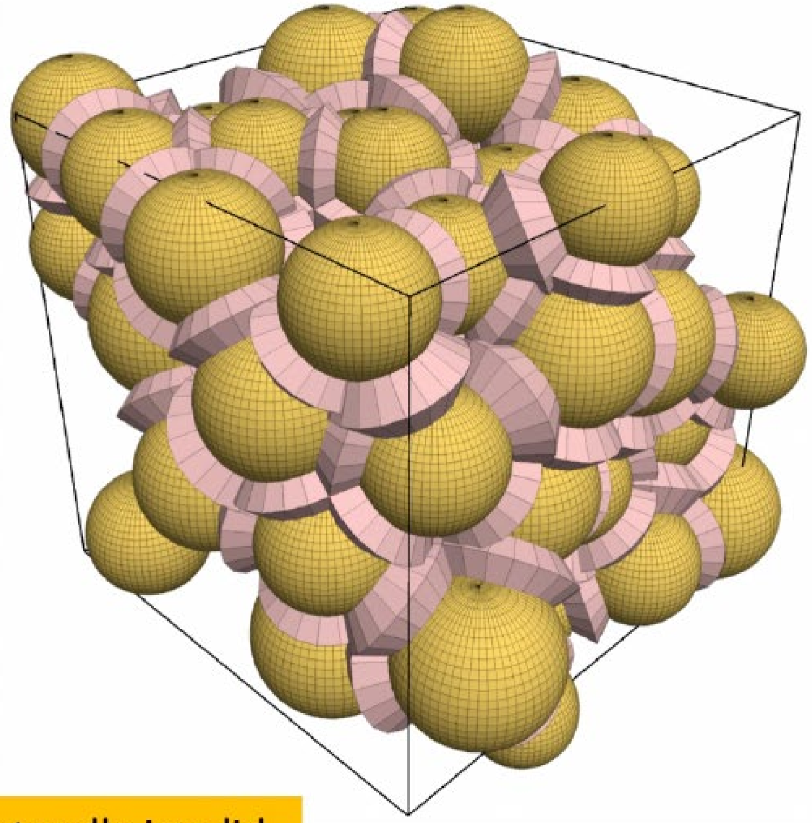
Microstructures (3D, invalid)

Not aesthetically pleasing, inelegant
But error is acceptable



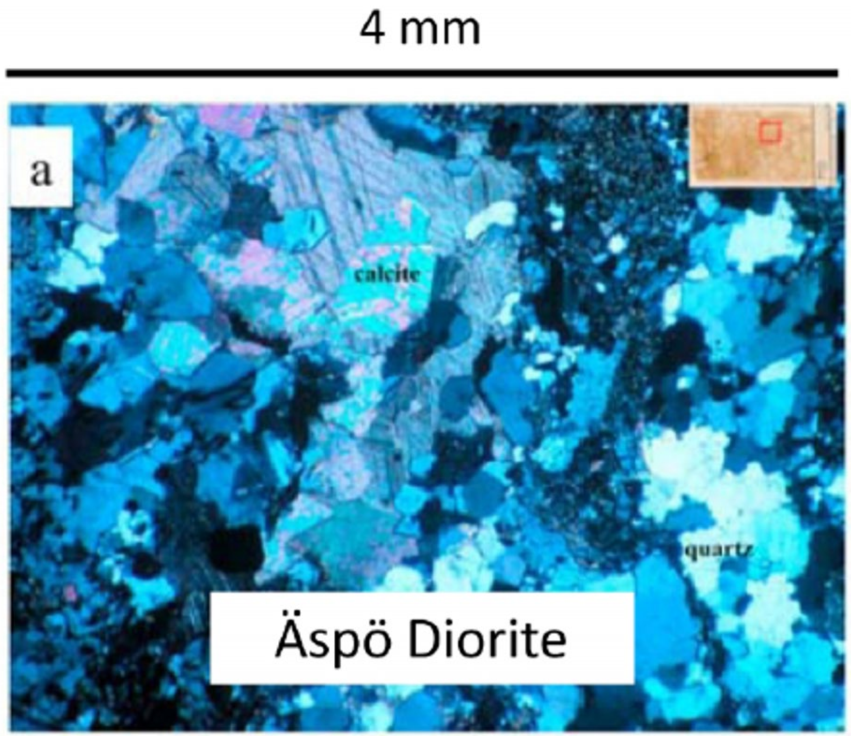


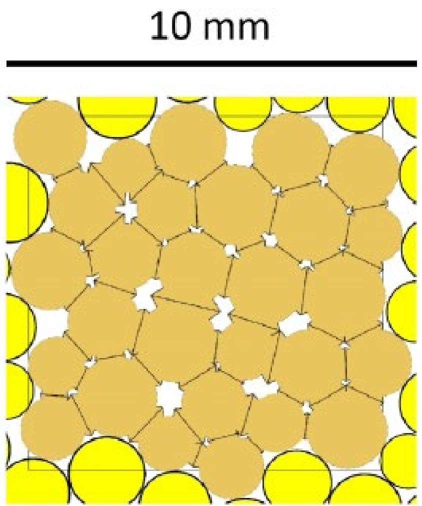
cube, s = 18 mm

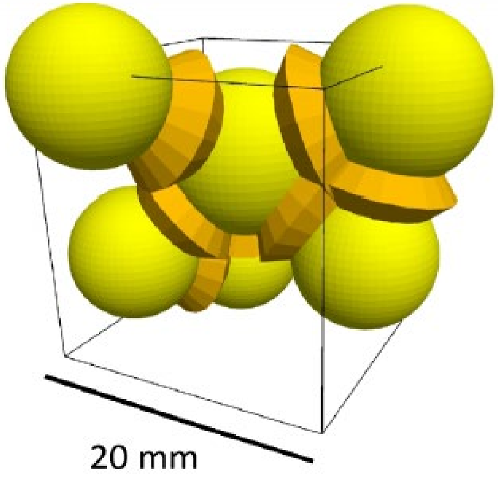


Microstructurally invalid

Microstructures (Äspö diorite & models)







Aspo diorite

$\rho = 2750 \ \text{kg/m}^3$

$\sigma_t = 10.1 \ \text{MPa}$

$\text{UCS} = 211 \ \text{MPa}$

$\sigma_{ci} = 94 \ \text{MPa}, \ \sigma_{cd} = 193 \ \text{MPa} \ (\text{UCS test})$

$E = 73.6 \ \text{GPa}, \quad \nu = 0.25$

$\sigma_f(7 \ \text{MPa}) = 252 \ \text{MPa}$

$\text{HB:} \ \sigma_c = 211 \ \text{MPa}, \ m_i = 10.7$

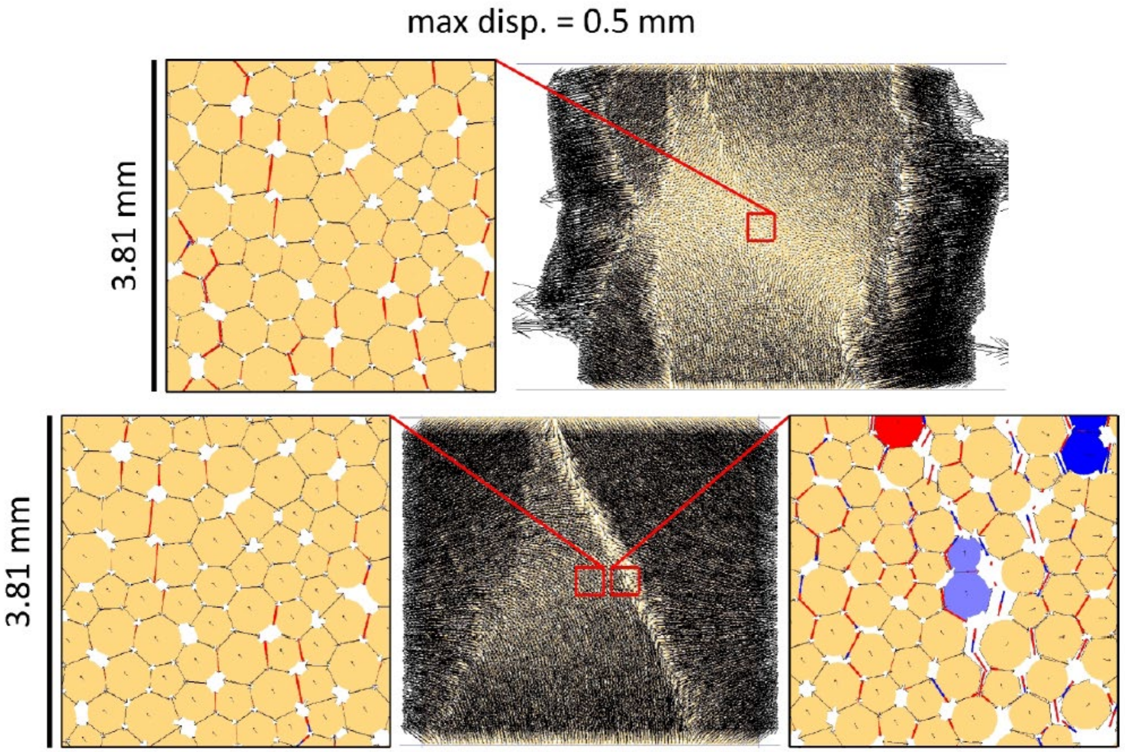
Match Young’s modulus, direct-tension & compressive strengths, slope of strength envelope up to 4-MPa confinement.

Underestimate crack-initiation stress & Poisson’s ratio

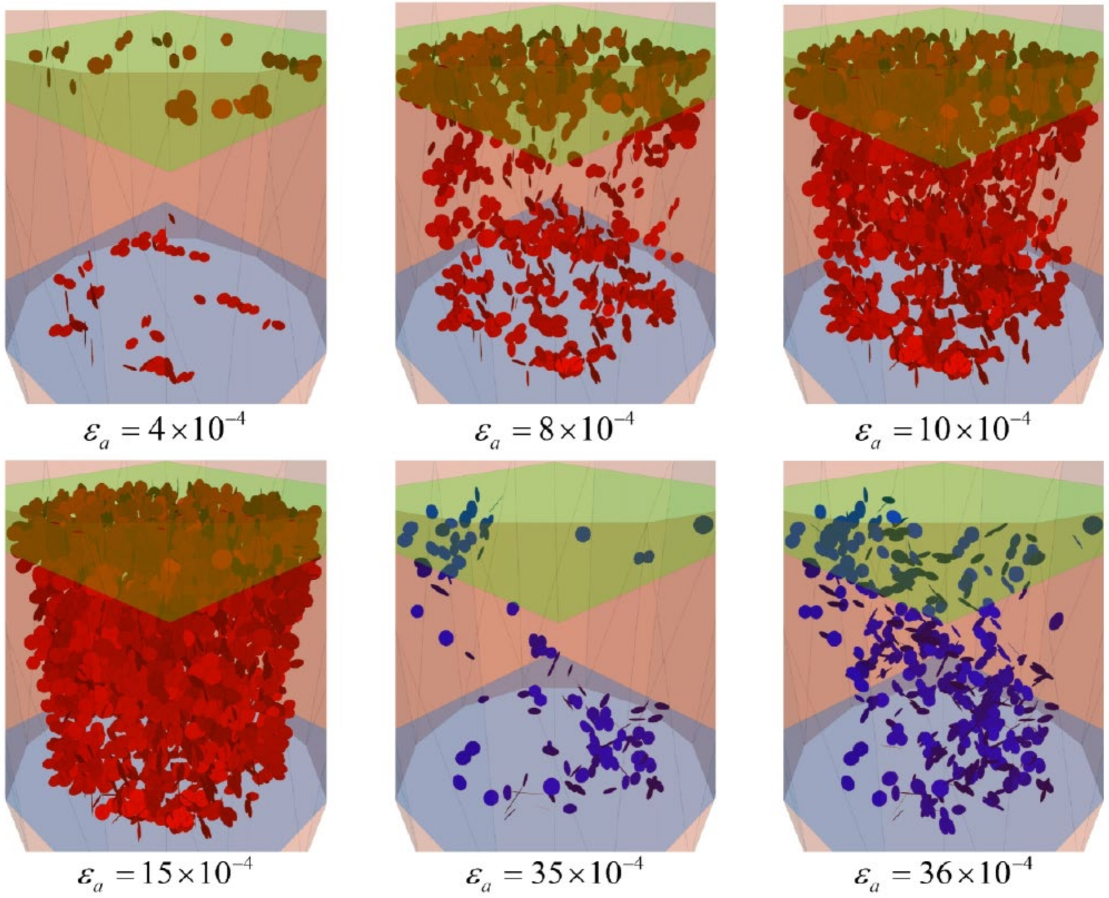
Axial splitting & shear bands (2D yes, 3D no)

Lab Tests (axial splitting & shear bands)

Axial splitting & shear bands (2D yes, 3D no)

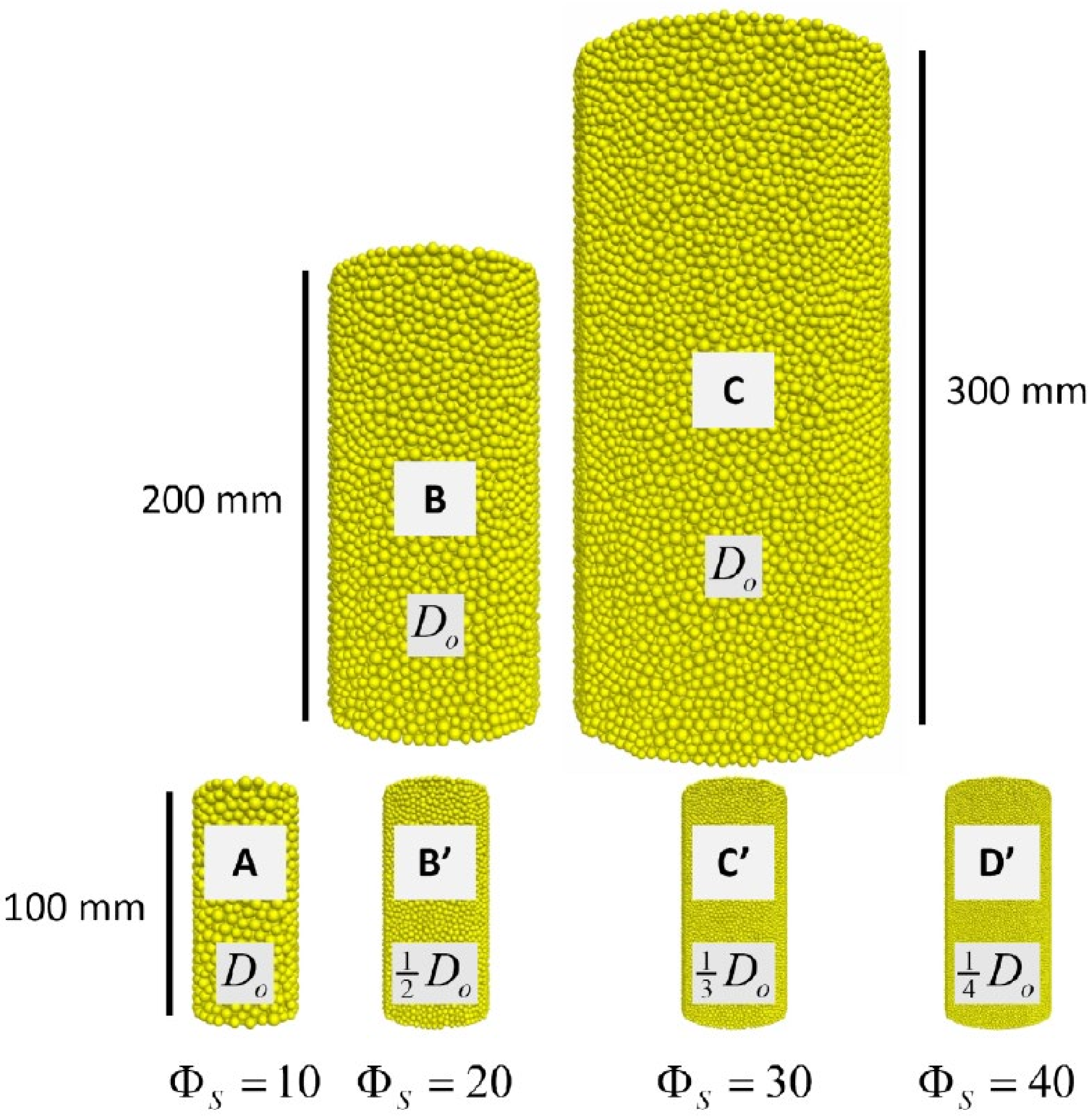


2D model



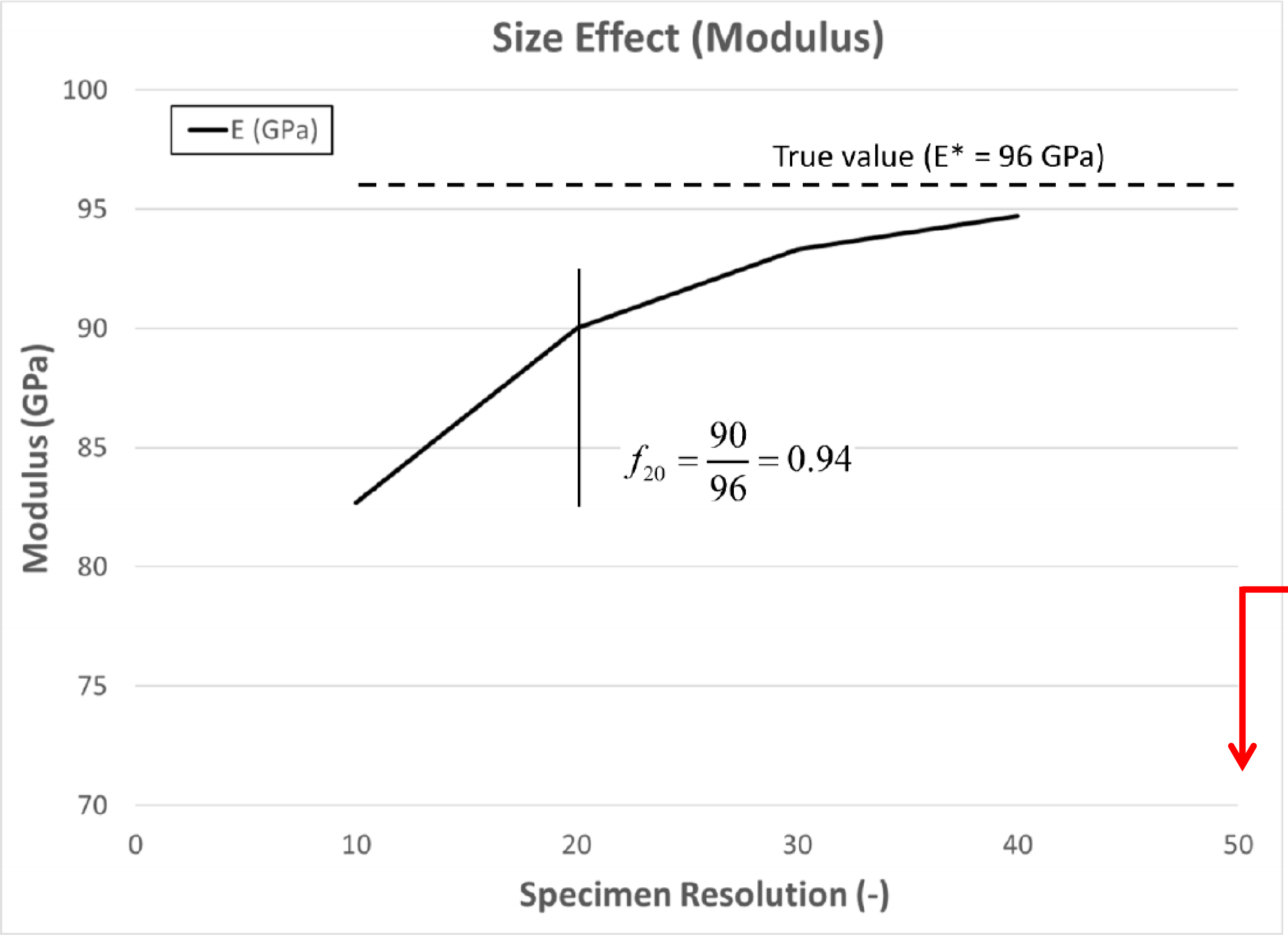
3D model

Lab Tests (3D, Size Effect)



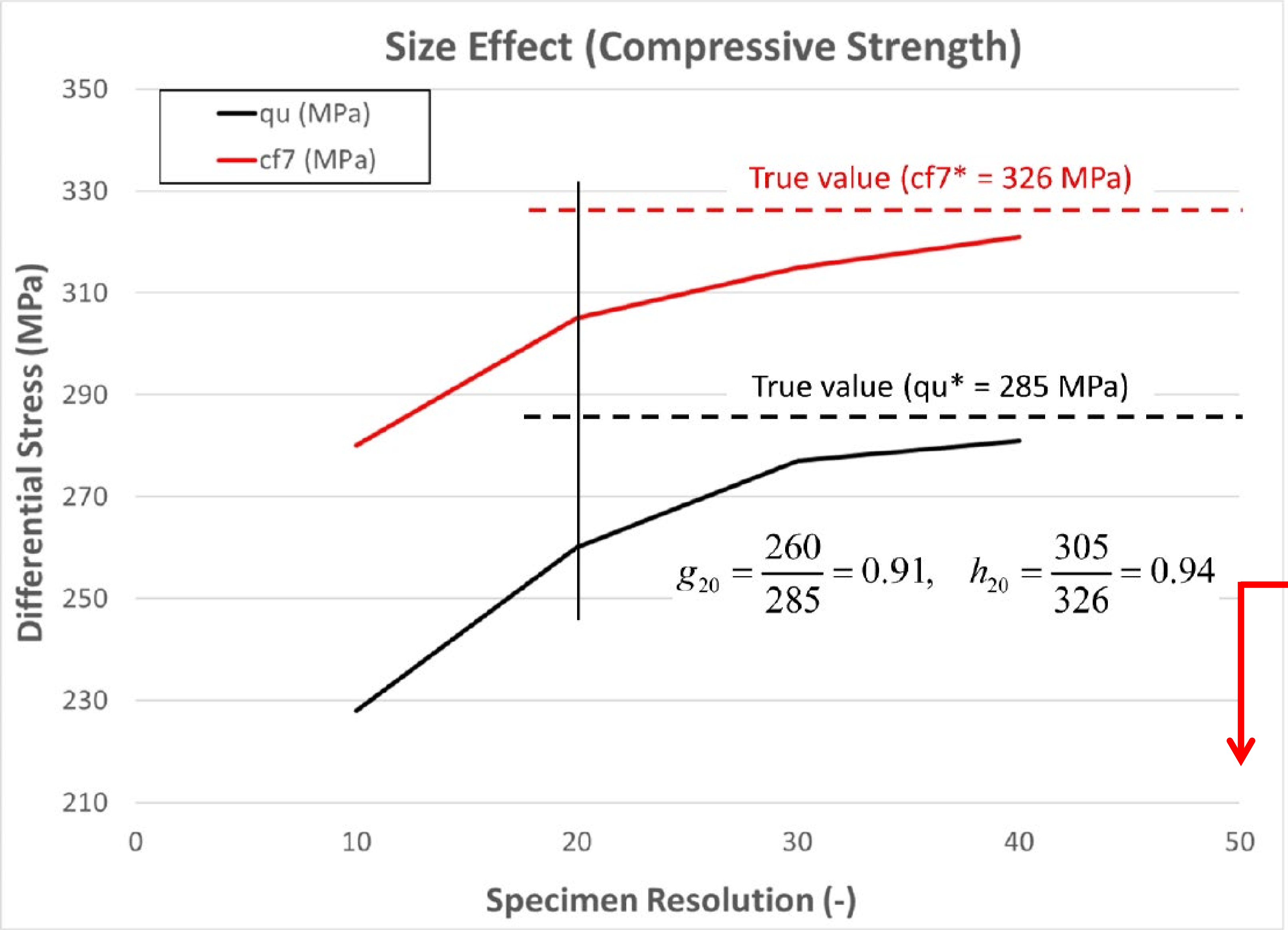
- Direct-tension strength & Poisson's ratio same for all specimens.
- Specimen resolution is controlling parameter for Modulus & Strength.
- Modulus & Strength increase with increasing specimen resolution, approach asymptotic value at resolution of 50 (next two slides).

Lab Tests (3D, Size Effect)



Representative volume

Lab Tests (3D, Size Effect)

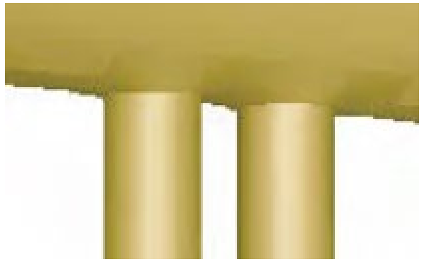


Representative volume

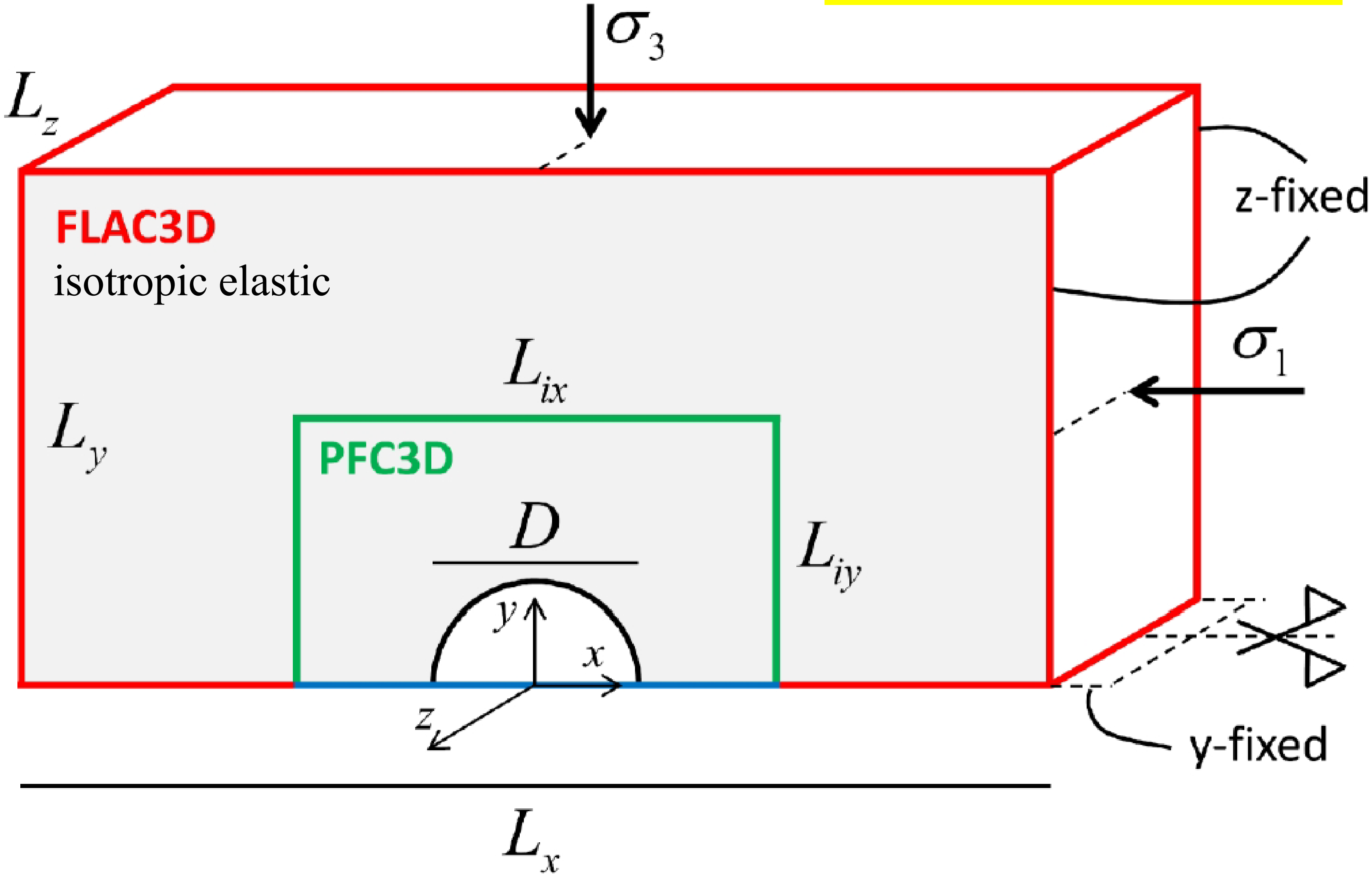
Borehole Models (coupled FLAC3D-PFC3D, quasi 3D)

Approximate conditions of APSE experiment (one hole at fixed depth)

QUALITATIVE comparison



Out of plane stress affects induced damage



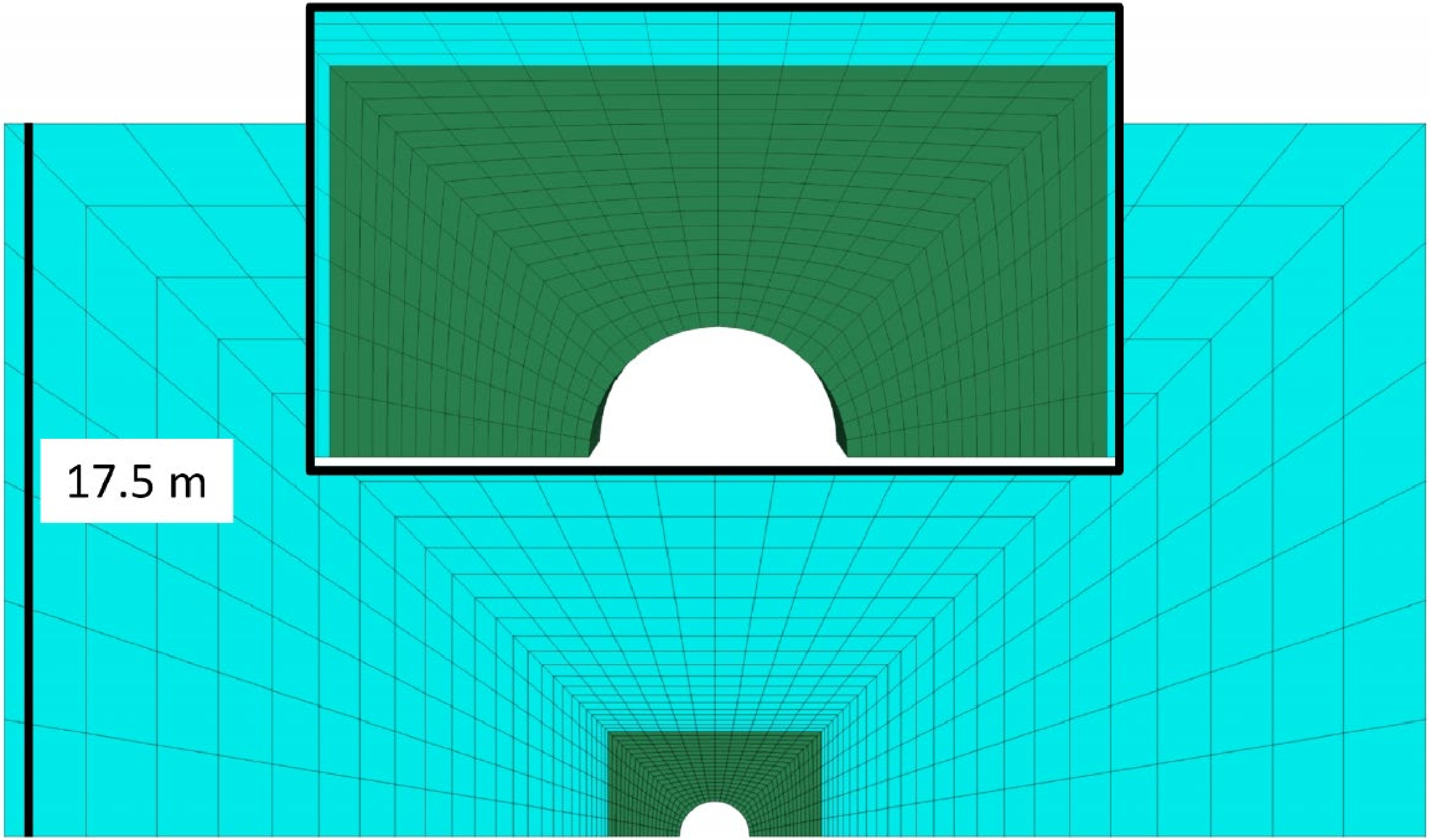
Borehole Models (modeling sequence)

- Install initial stress field
- Excavate hole (delete particles, relax boundary support forces)
- Reduce material strength or increase external load

- Quasi-static loading

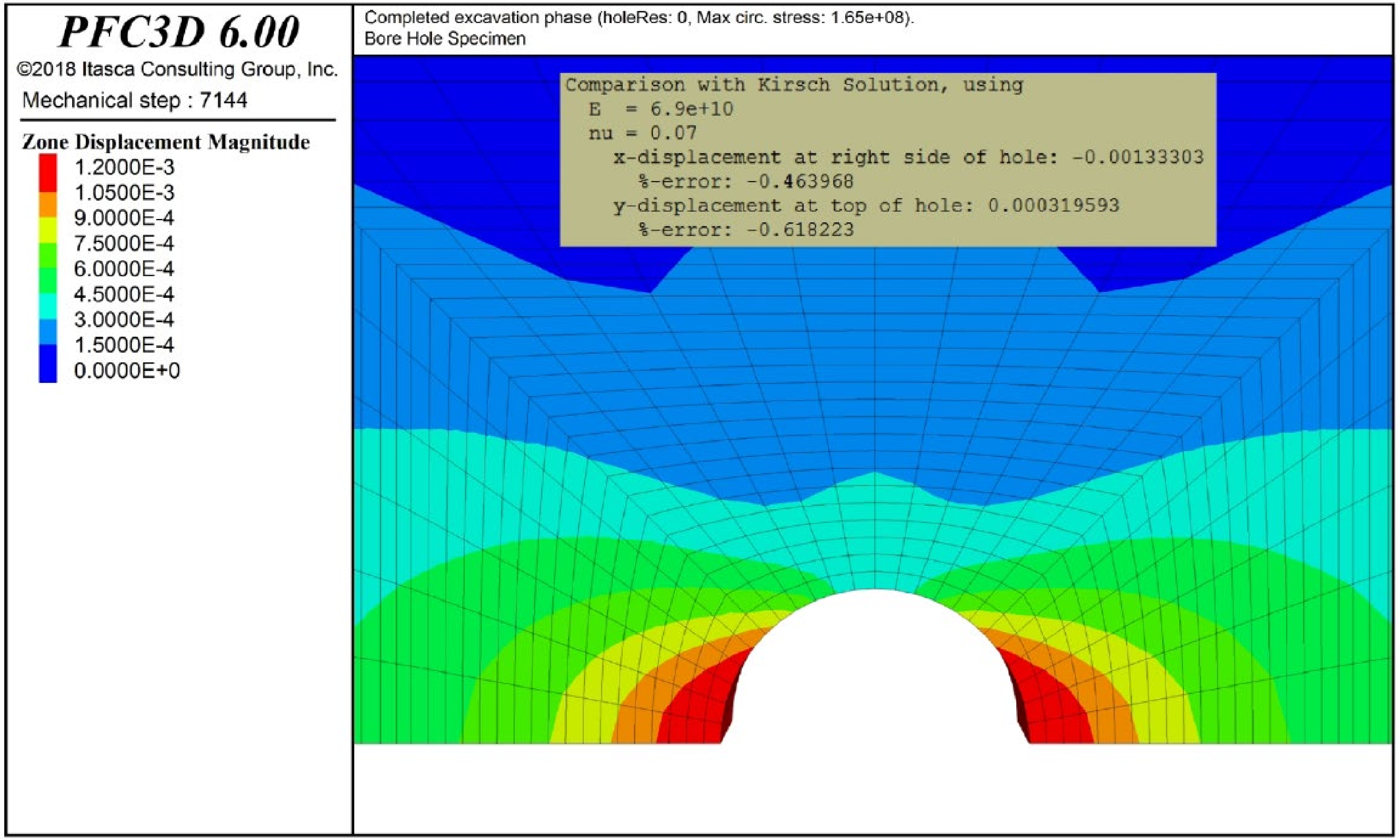
- Observe damage (bond breakages in FJ material)

Borehole Models (coupled FLAC3D-PFC3D, quasi 3D)



Borehole Models (coupled FLAC3D-PFC3D, quasi 3D)

FLAC3D grid is sufficient to resolve deformation field, matches Kirsch solution

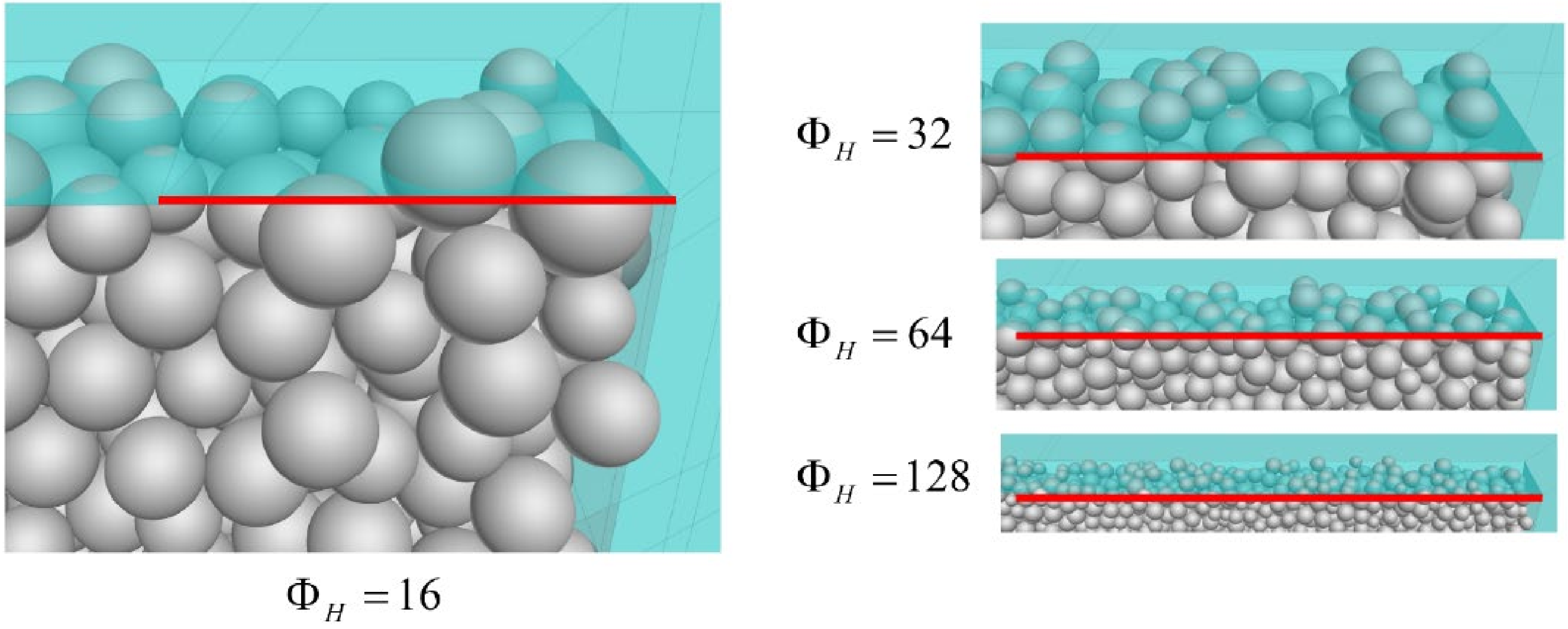


Borehole Models (PFC3D region)

Vary average grain diameter from 108 to 9 mm (hole resolution from 16 to 194)

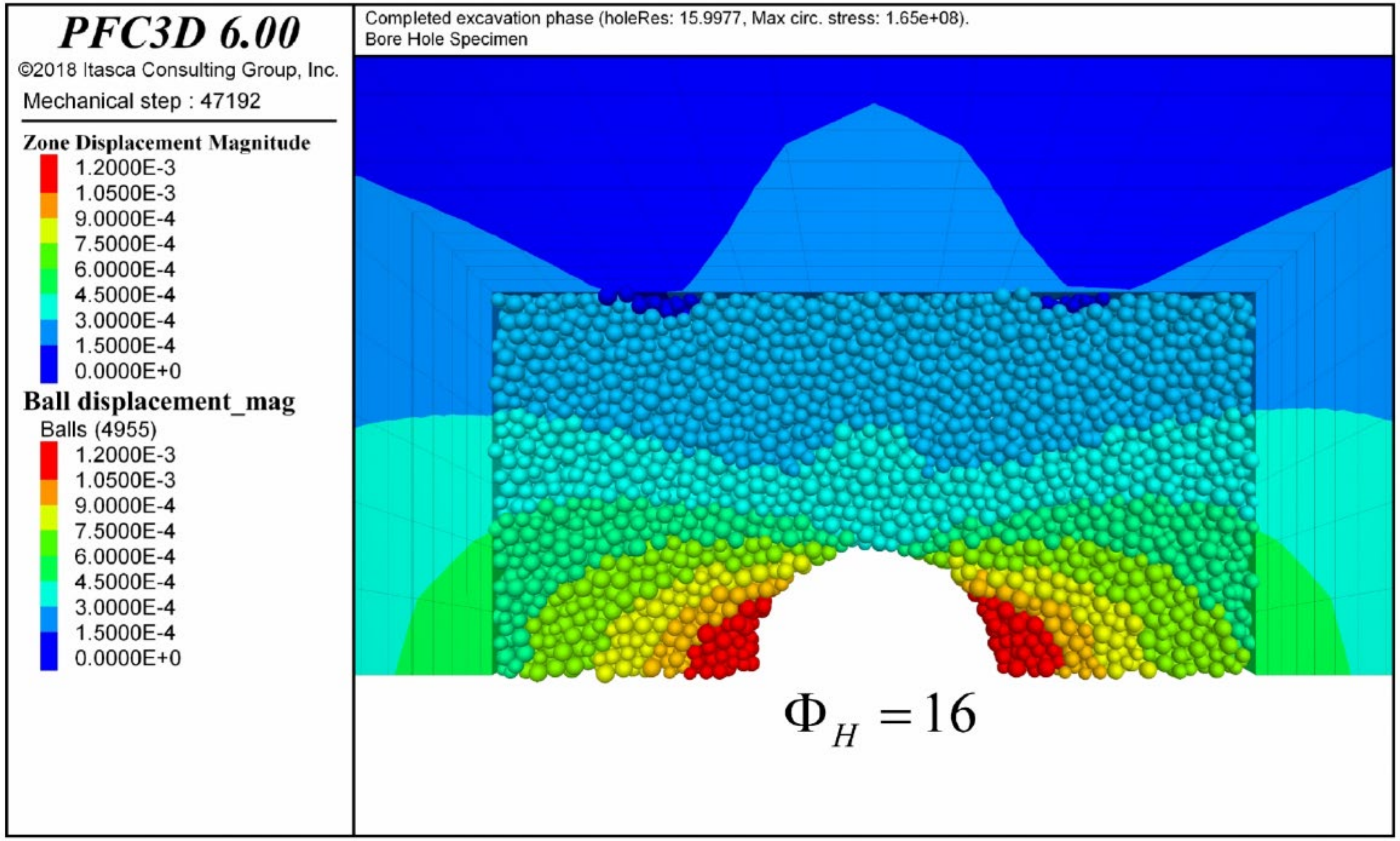
Maintain four balls through thickness

4 balls through thickness, zone edge (red)



Borehole Models (PFC3D region)

Displacement field is compatible across coupling interface.



Borehole Models (PFC3D region)

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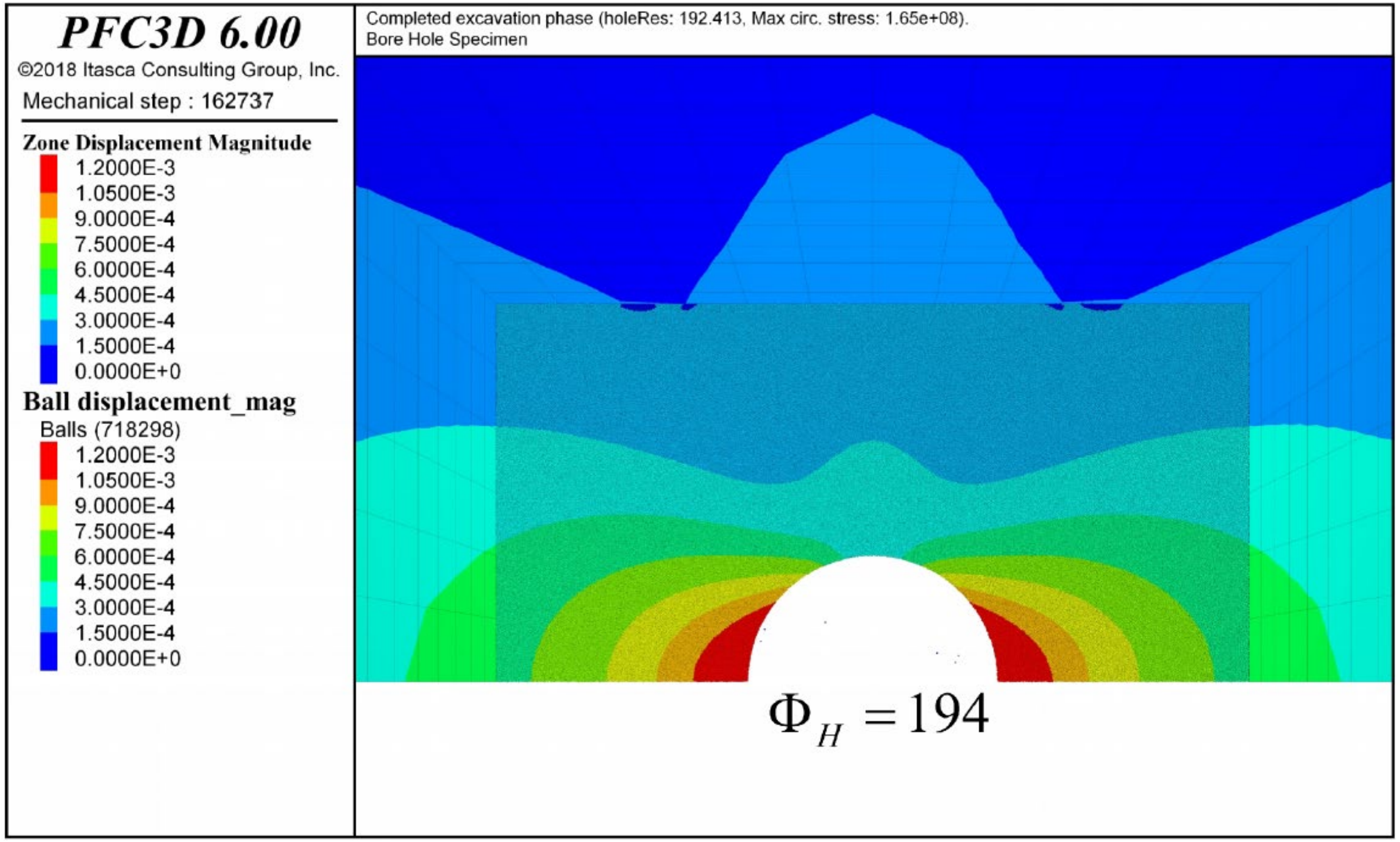
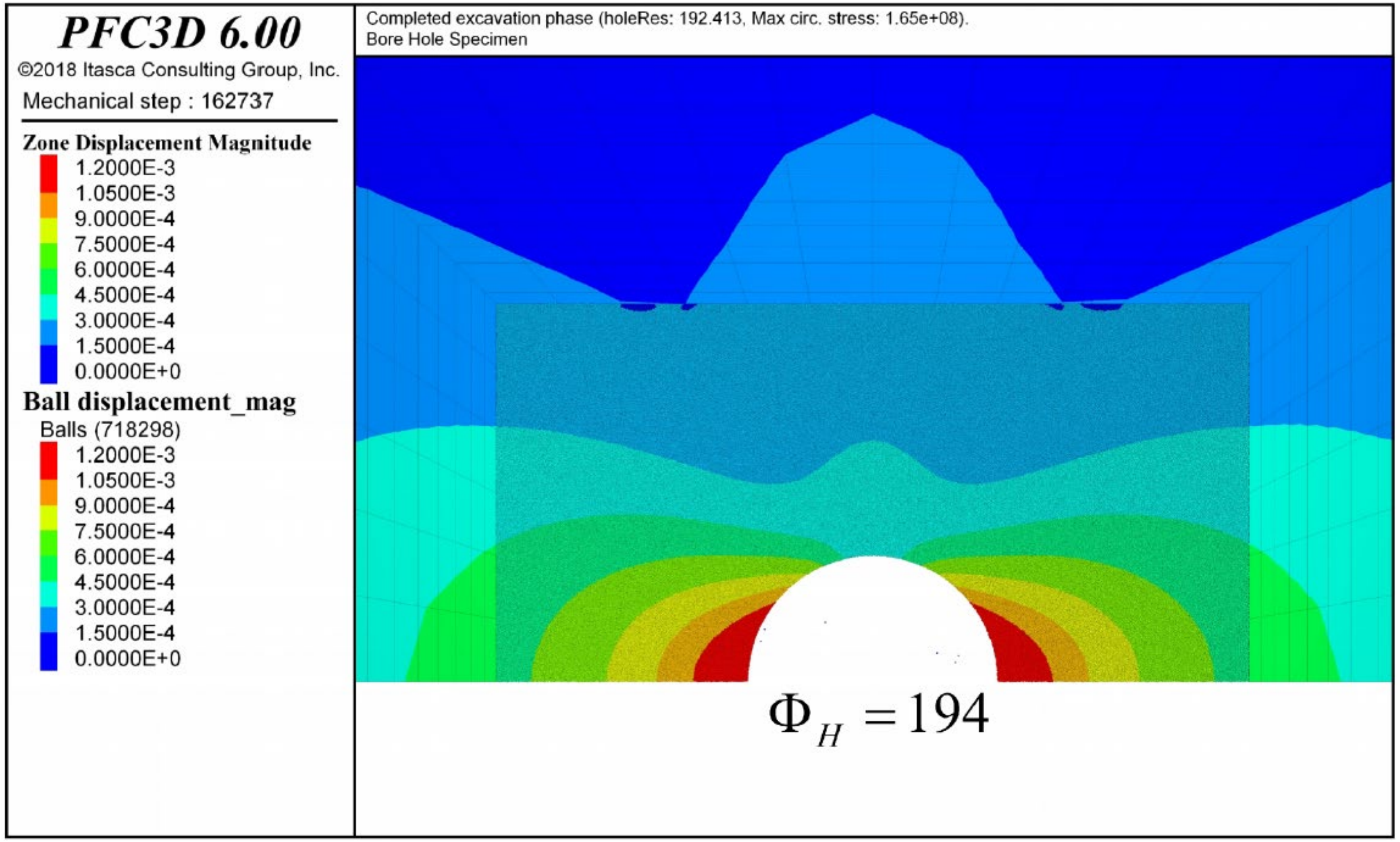


718,000 balls
48-hour run time

Borehole Models (PFC3D region)

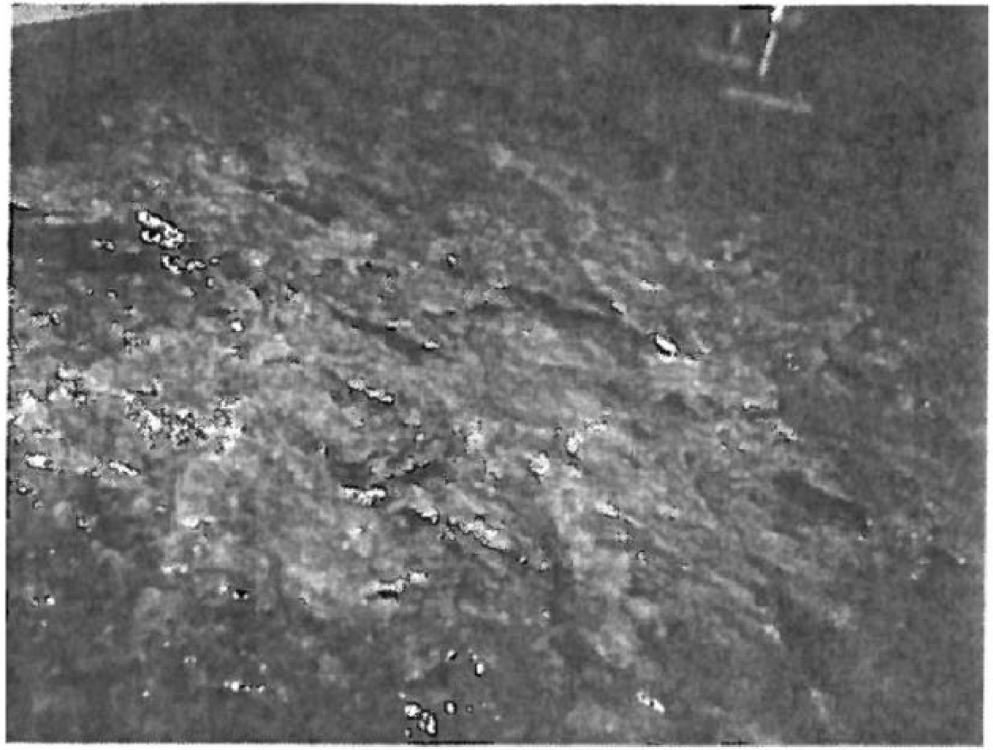
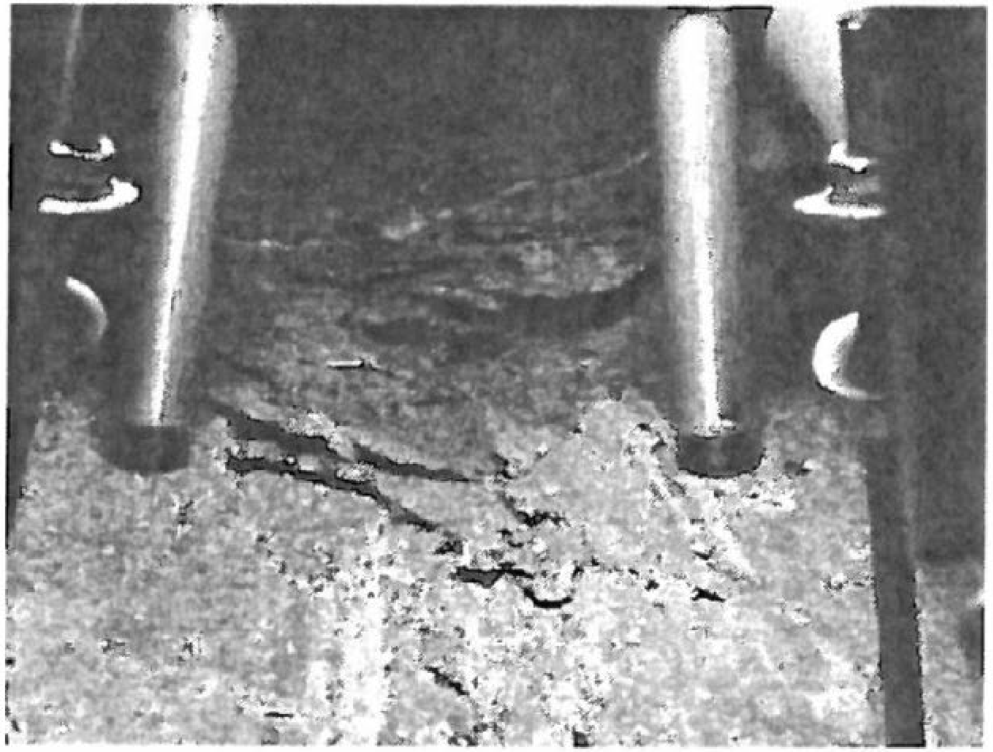
Deformation field matches Kirsch solution.

Correct boundary conditions to the PFC3D region => Can study damage!



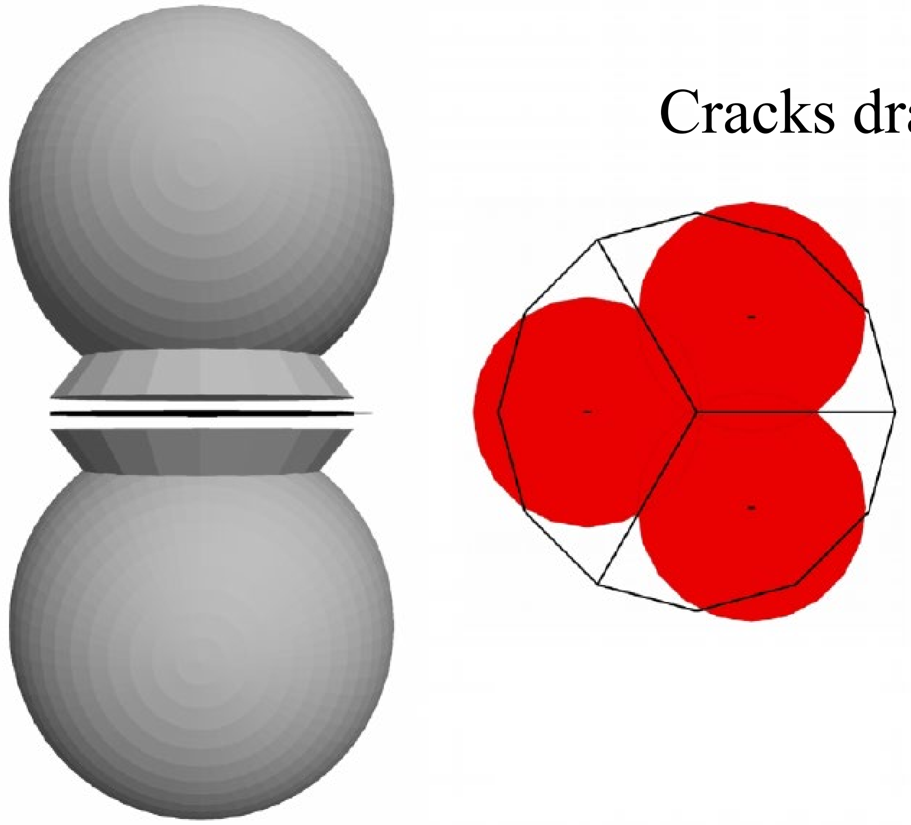
Borehole Models (APSE Experiment)

Chips have formed in tension, initiates when tangential stress reaches 59% of UCS
Distinct stress threshold

Borehole Models (Damage Plots)

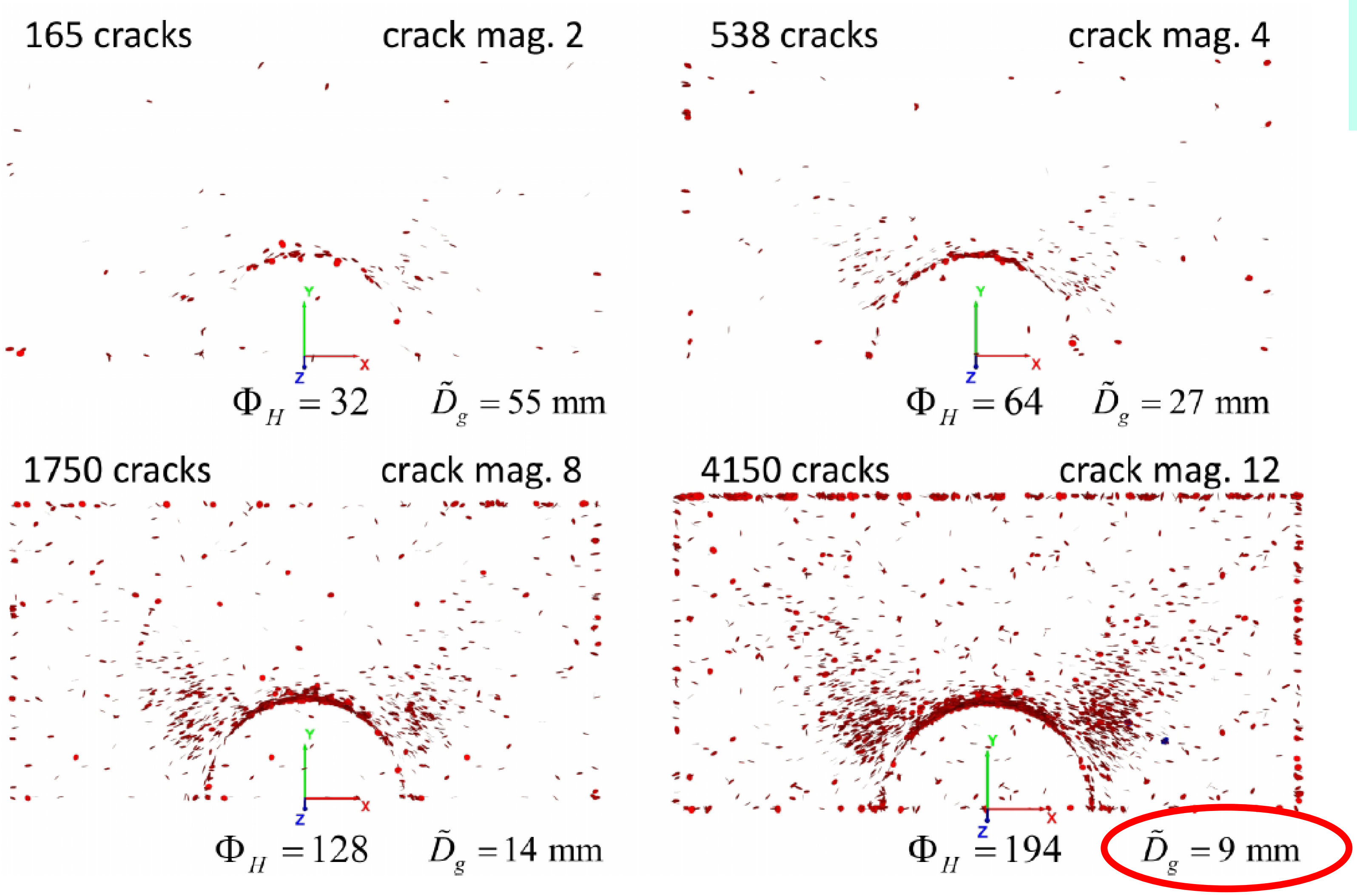
Damage consists of broken bonds at each flat-joint element



Cracks drawn at true size

When cracks are magnified, crack density cannot be visually assessed

Borehole Models (Damage as function of hole resolution)



Damage increases as hole resolution increases, with gradual formation of a spalling zone & two damage lobes.

Expect best match to rock behavior when grain size equals that of the rock.

Äspö diorite grain size from 0.1 to 5 mm

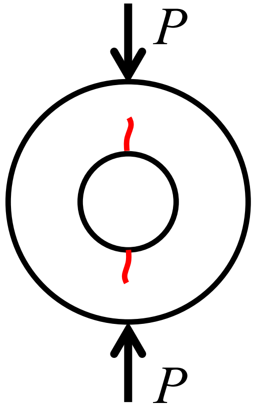
Borehole Models (Damage as function of hole resolution)

Similar size effect for:

Attributed to process-zone formation before breakdown

Indirect Tension test

$$\Phi_H \uparrow \Rightarrow P^* \downarrow \text{ (weaker)}$$



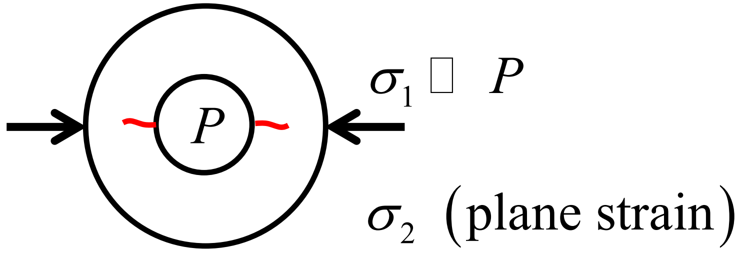
Different hole sizes, larger holes are weaker.

Kaklis et al. (2019)

Cavity Expansion test

$$\Phi_H \uparrow \Rightarrow P^* \downarrow \text{ (weaker)}$$

P* is breakdown pressure



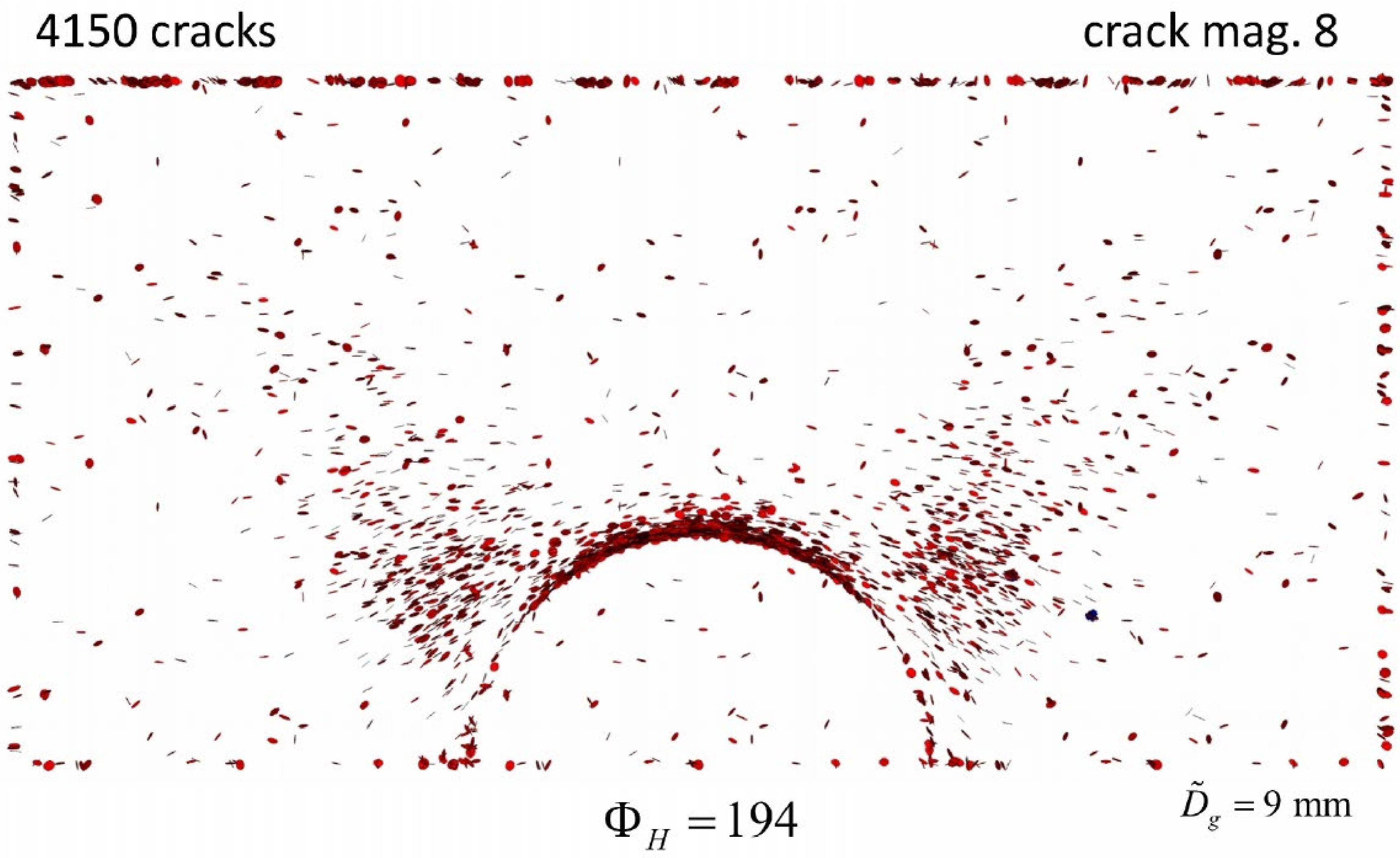
Different hole sizes, larger holes are weaker.

Tarokh et al. (2016)

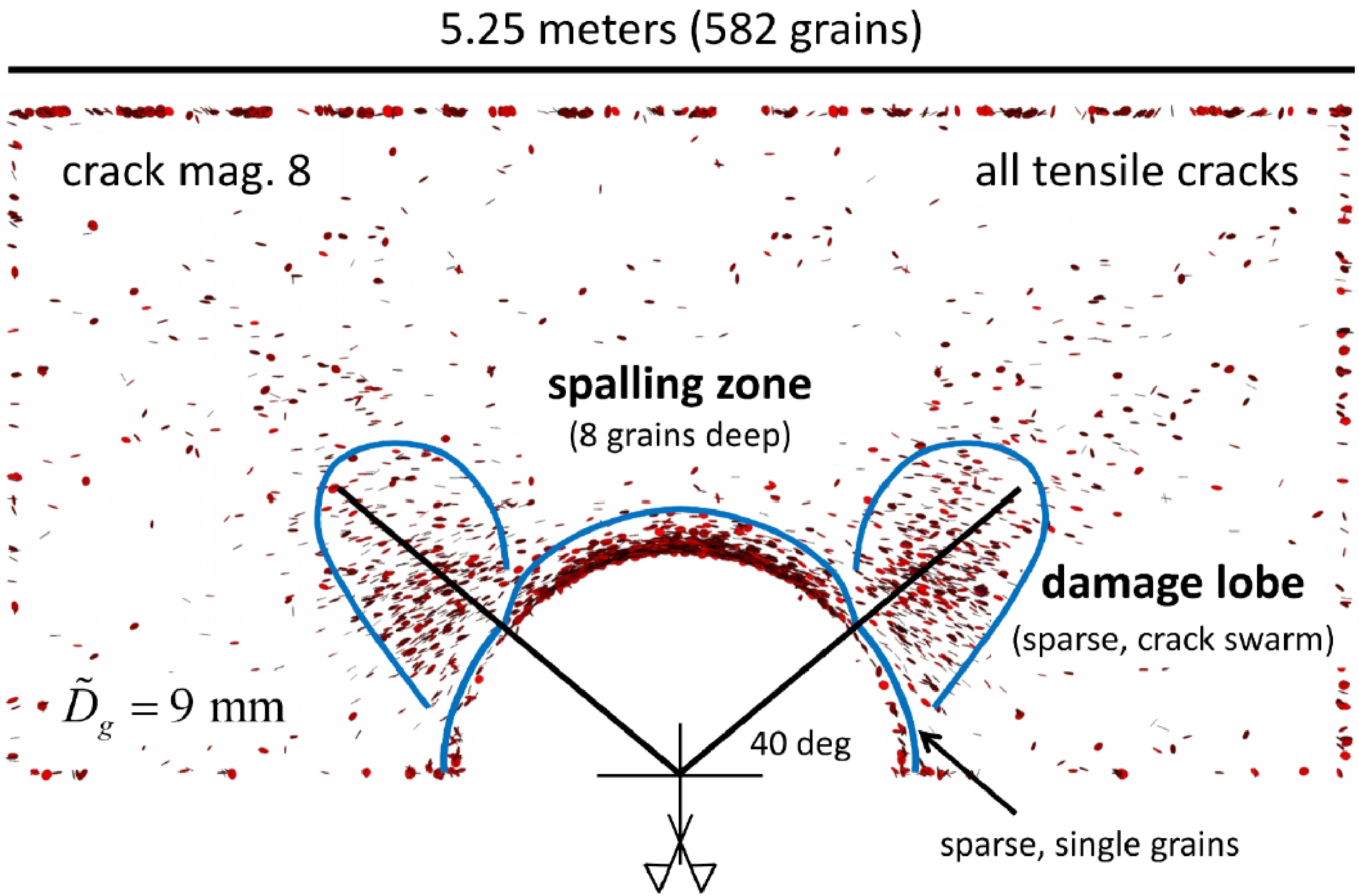
Similar process may be occurring for spalling zone

Borehole Models (Damage after excavation)

Spalling zone & two damage lobes



Borehole Models (Spalling zone & two damage lobes)

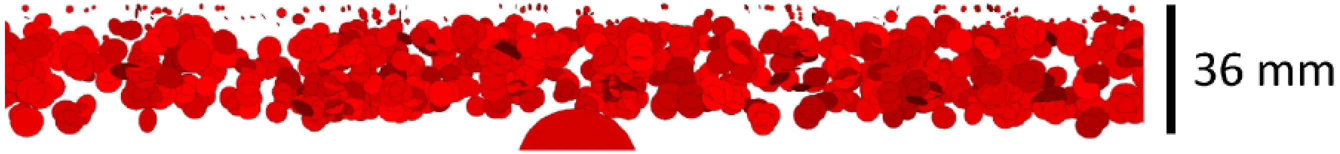


Borehole Models (Damage after excavation)

Damage is uniform through thickness, tensile and parallel to compressive force chains.

side view

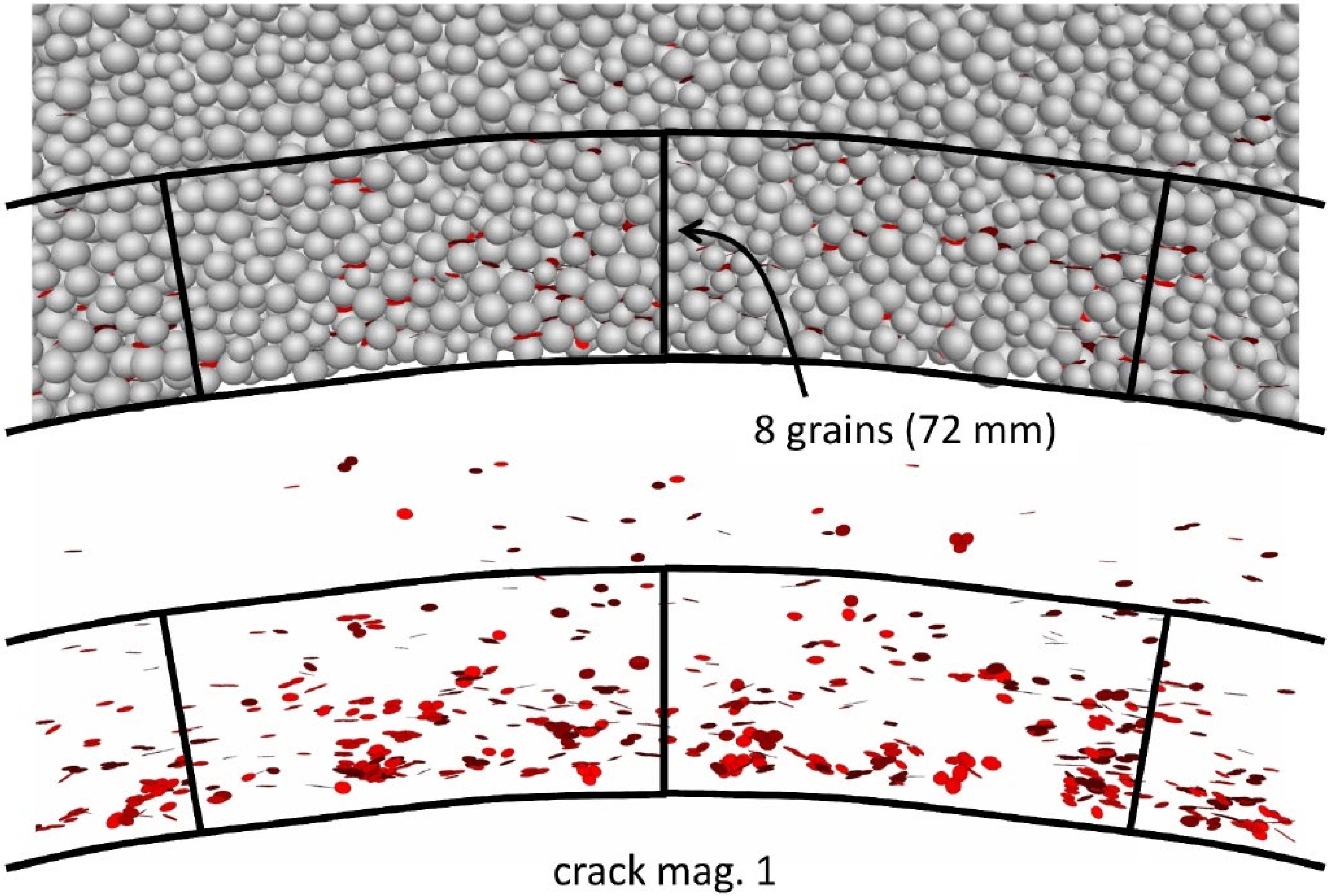
looking up



APSE: chips formed on boundary, tangential to hole wall, formed in tension

Borehole Models (Spalling zone)

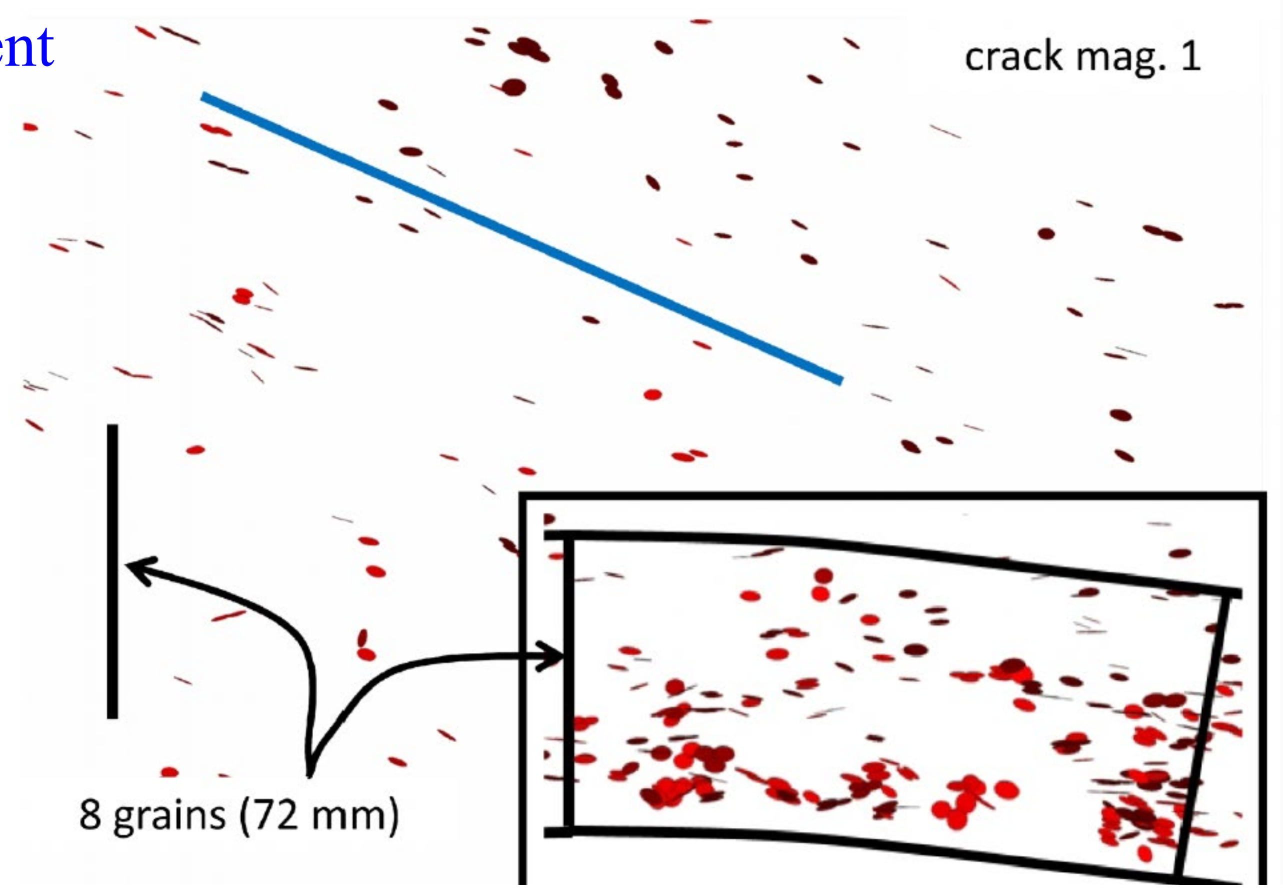
Spalling depth is 8 grains over 100-degree sector, then reduces to single grains



Borehole Models (Damage lobes)

Damage lobes consist of a crack swarm. Crack density and dilation are greater in the spalling zone than in the damage lobes, and swarm cracks are aligned with compressive force chains.

force-chain alignment
(blue line)



damage lobe

spalling zone

Borehole Models (Damage lobes)

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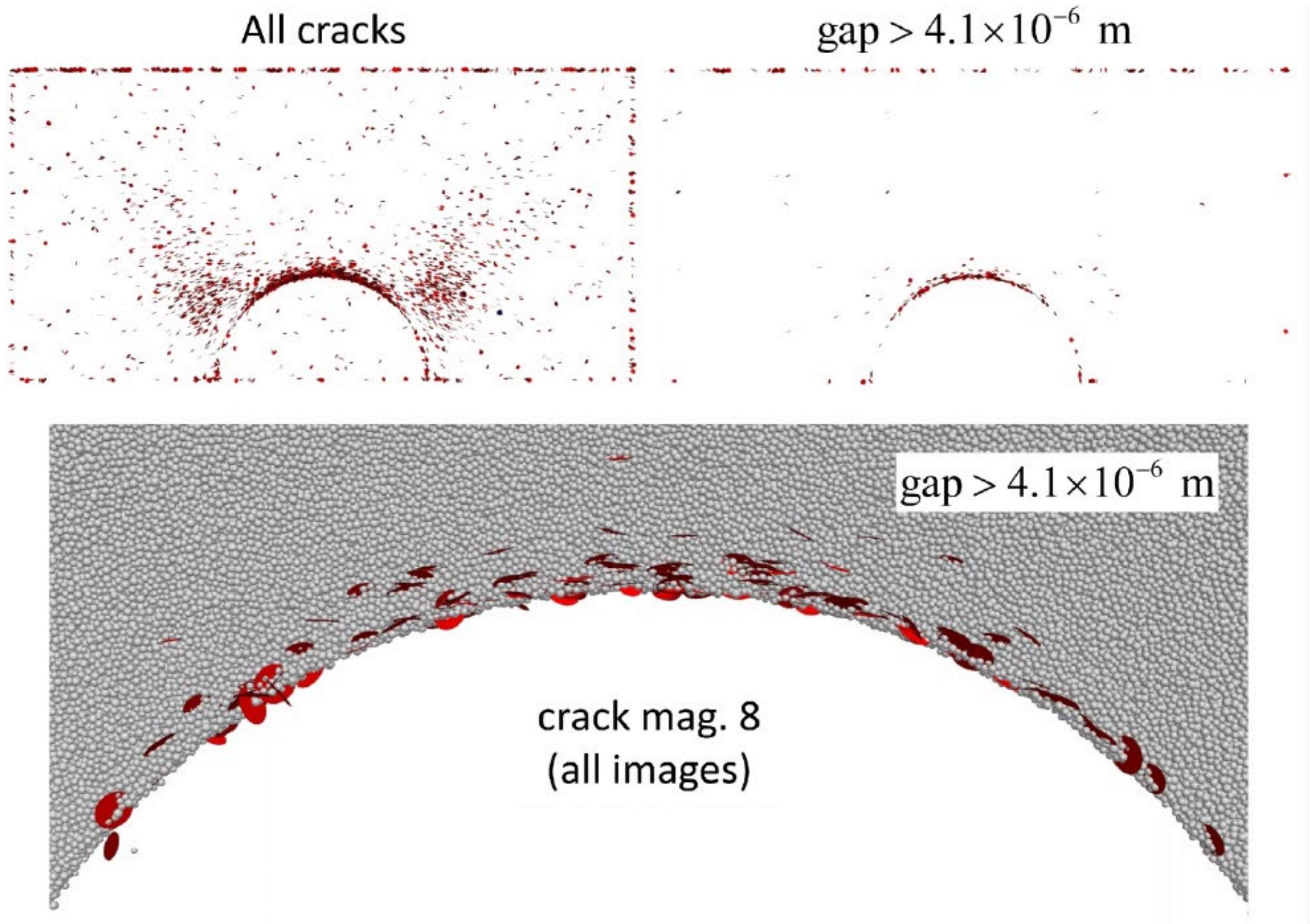
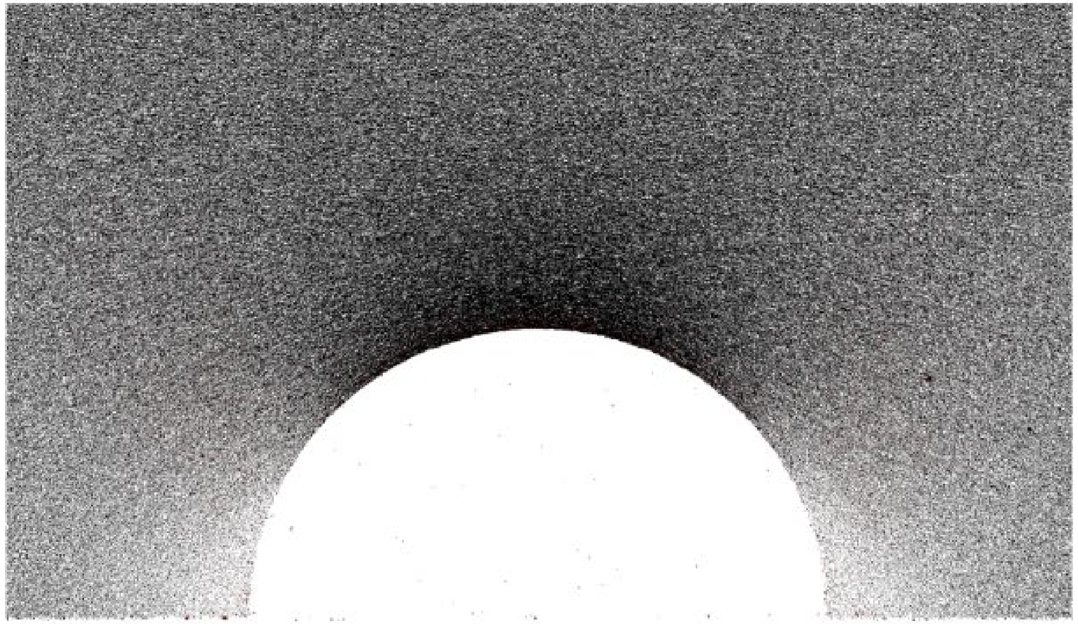
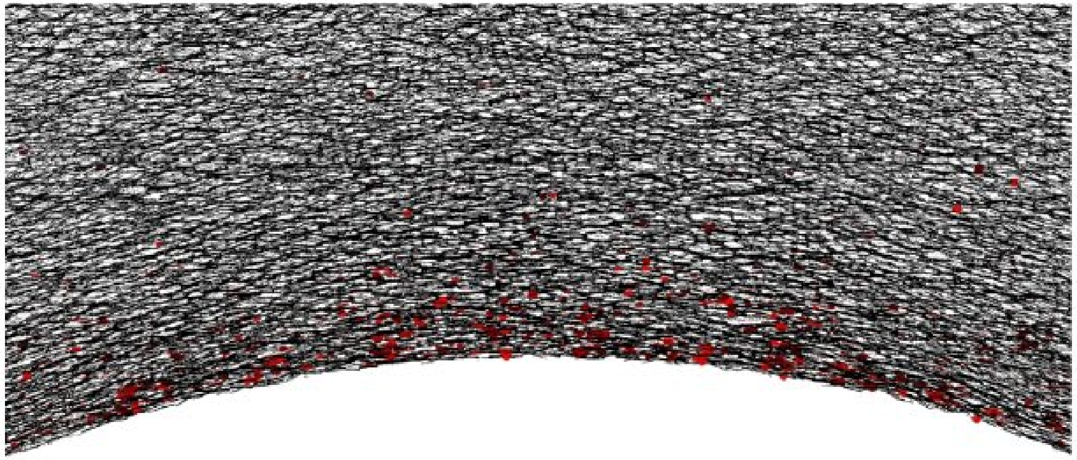


Borehole Models (Spalling zone)

Spalling zone corresponds with early stage of rock mass yielding before a well-defined v-shaped notch has formed. Material in spalling zone has not yet softened sufficiently to divert load further into the rock.

crack mag. 1





Borehole Models (Damage Lobes)

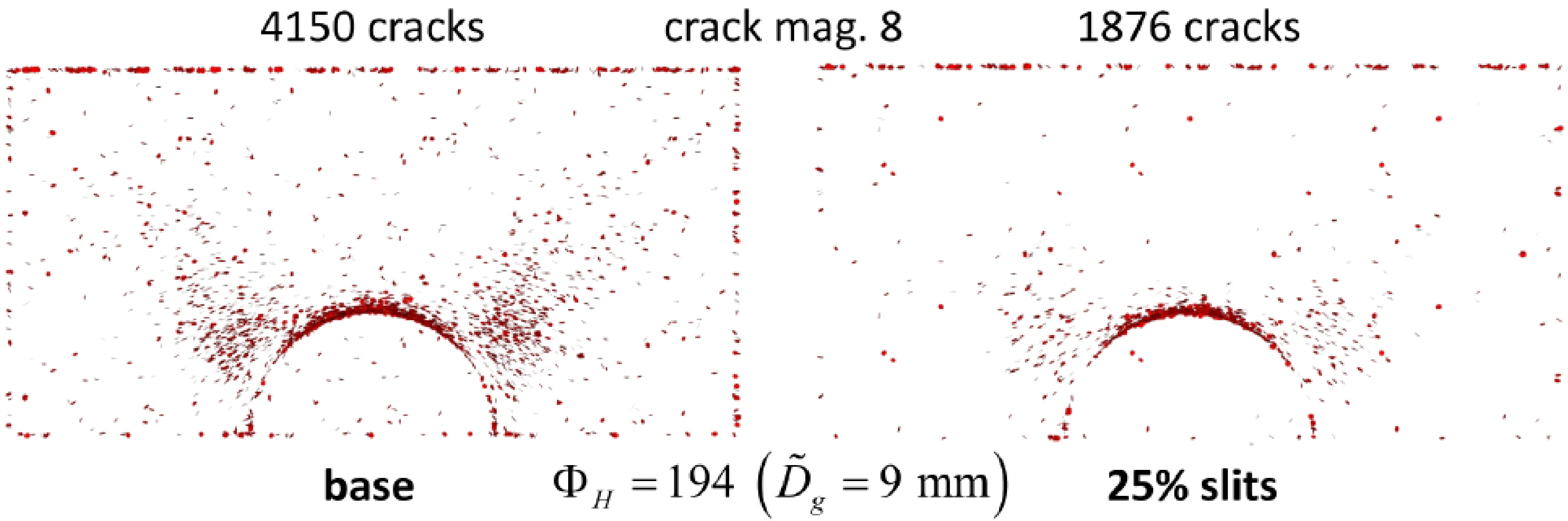
Damage lobes may be present in the rock around a spalled region but have not yet been observed. The relatively low crack density suggests that this damage should have a negligible effect on borehole strength and permeability, as the cracks are not well connected.

Damage lobes: real or model artifact?

Would be interesting to explore this further. . .

Borehole Models (Effect of 25% slits)

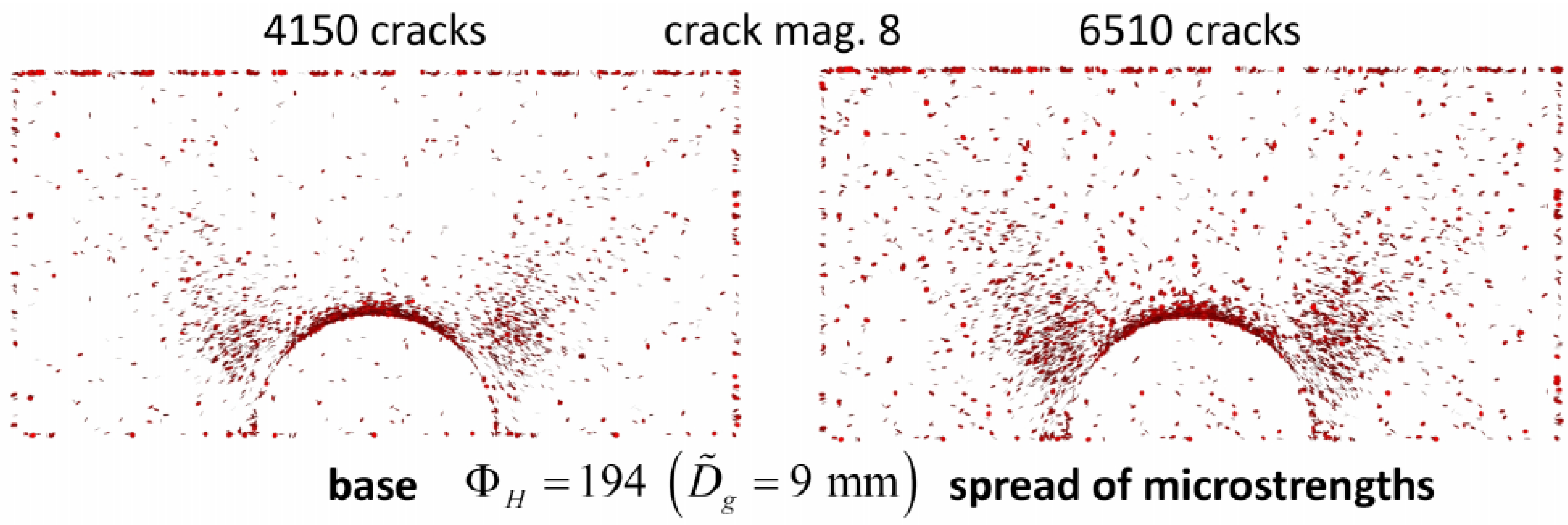
Decreases the damage density without affecting overall damage characteristics. Some of the induced deformation is being taken up by sliding instead of cracking, thereby reducing the damage density.



$\Phi_H = 194 \left(\tilde{D}_g = 9 \text{ mm}\right)$

Borehole Models (Effect of distribution of microstrengths)

Increases the damage density without affecting overall damage characteristics. Damage increases because the weaker contacts fail at lower loads.



Conclusions

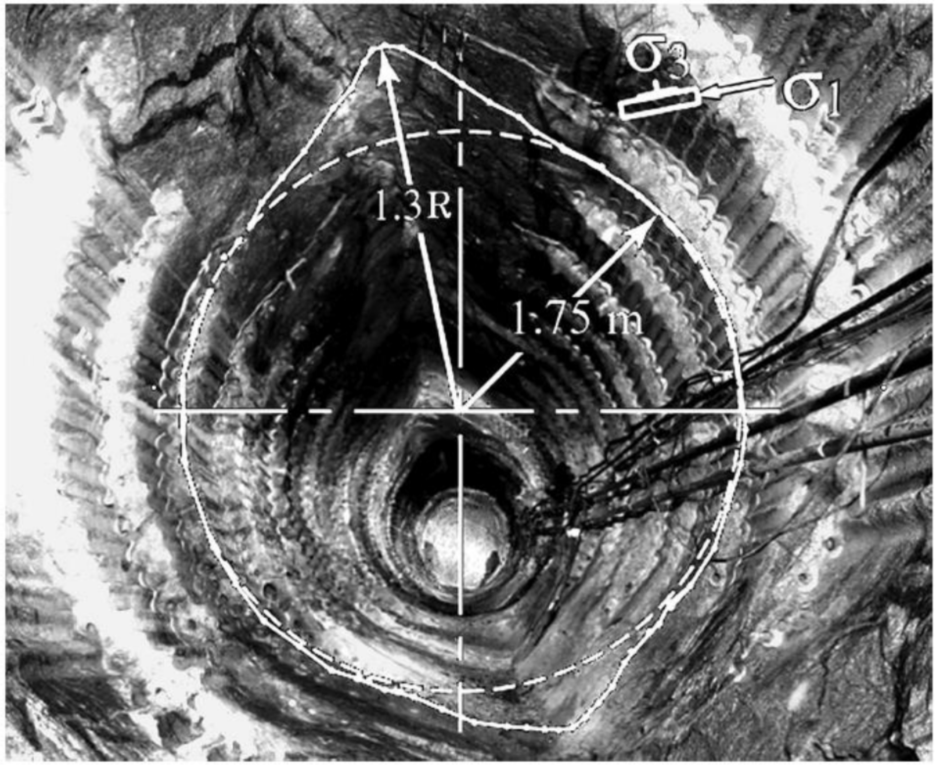
- Both 2D & 3D flat-jointed materials can match direct-tension and triaxial response of Äspö diorite.

- Borehole models exhibit spalling zone & two damage lobes, which become more clearly delineated when grain size is reduced.

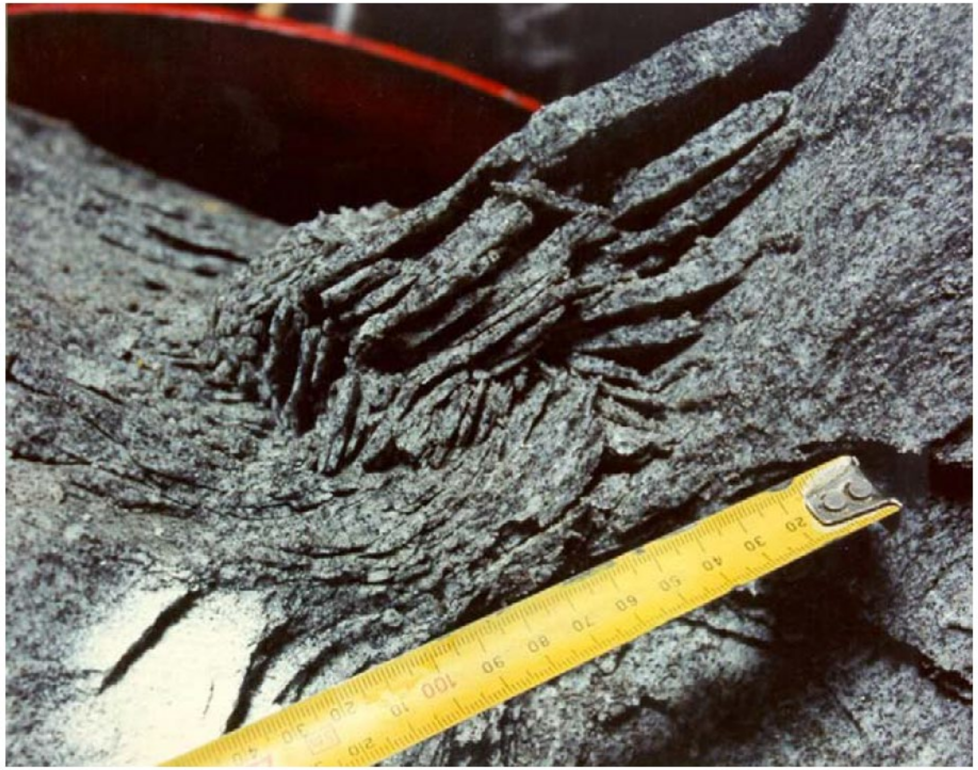
- Can now get to 9-mm grain size. Smaller grain size when PFC3D with MPI is ready.

Ongoing Work

Model Mine-By Experiment. . .



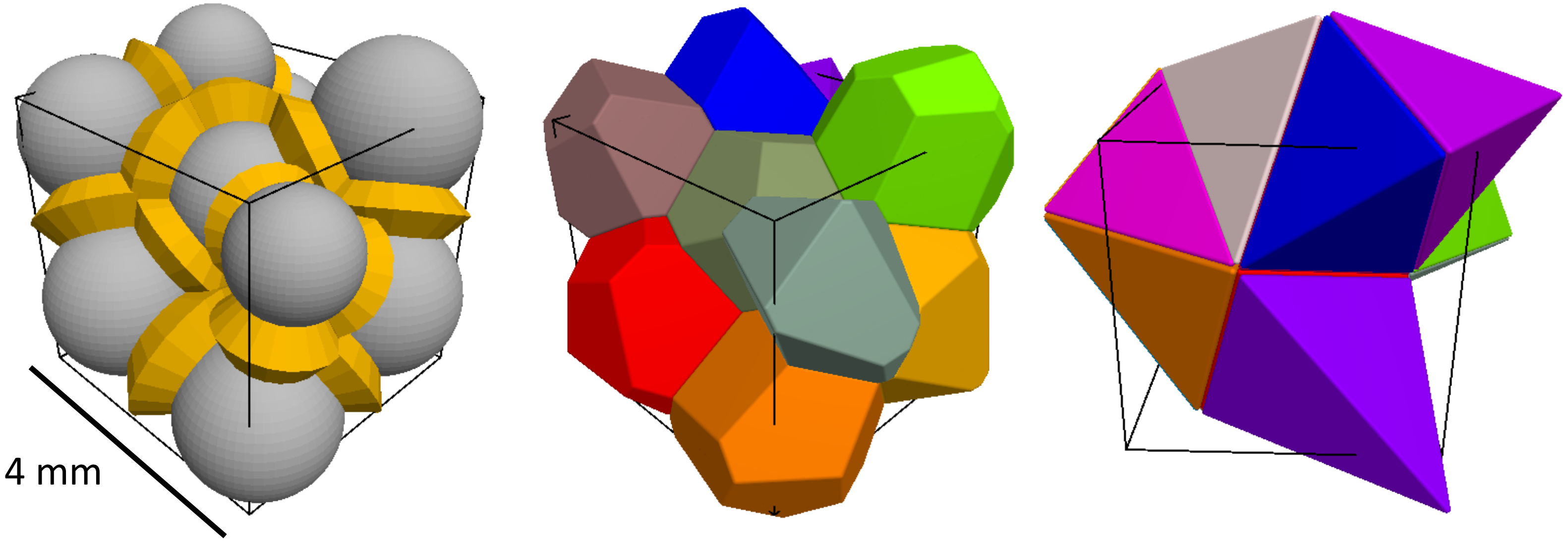
Mine-By Tunnel



Notch Tip

Ongoing Work

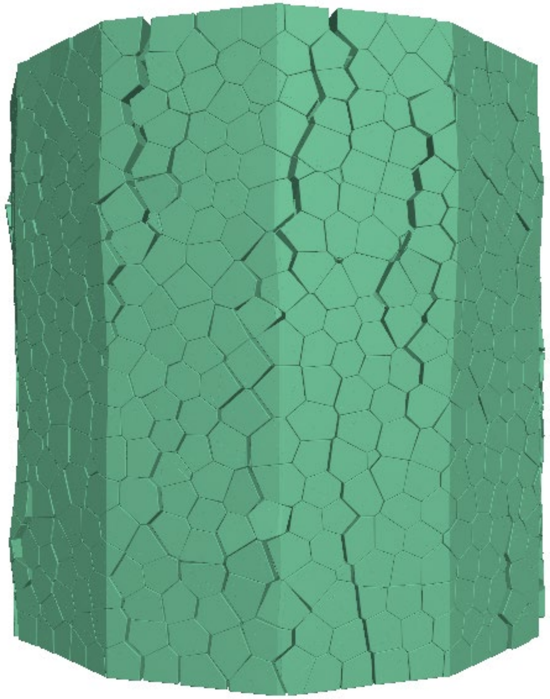
. . .with spherical, Voronoi and tetrahedral grains



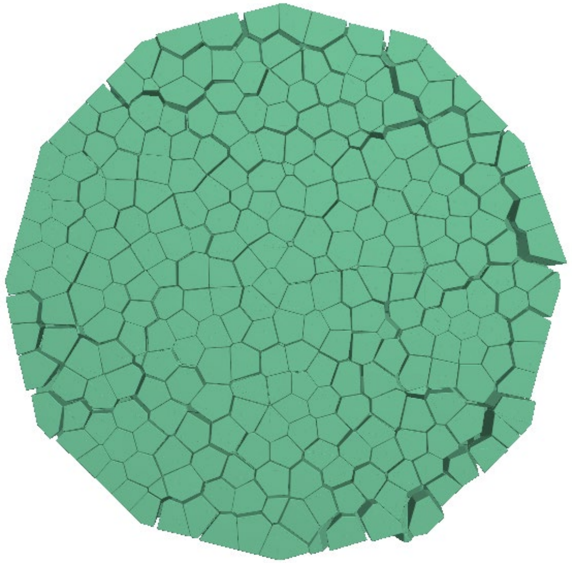
Ongoing Work

Axial splitting during UCS test

side view



top view



Stay tuned, more to come. . .