ITASCA
Consulting Group, Inc.

PFC (Particle Flow Code): Historical Development and Engineering Applications

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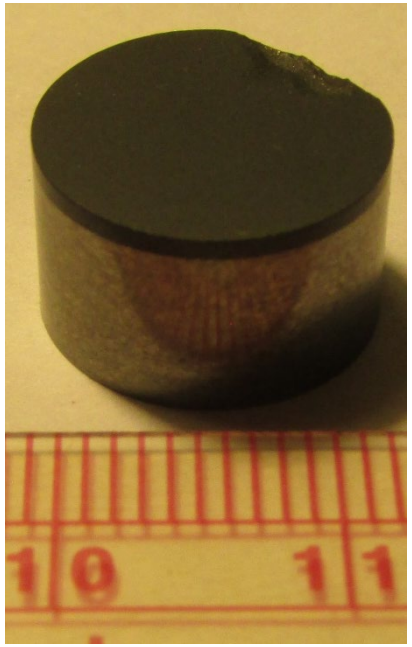
PFC Workshop
HydroChina - Itasca R&D Center, Hangzhou, China
23 May 2019

Rock Cutting Excerpt

Engineering Applications (Fracture & Flow Example)

Torrey Buff sandstone

rock-cutting test (dry)



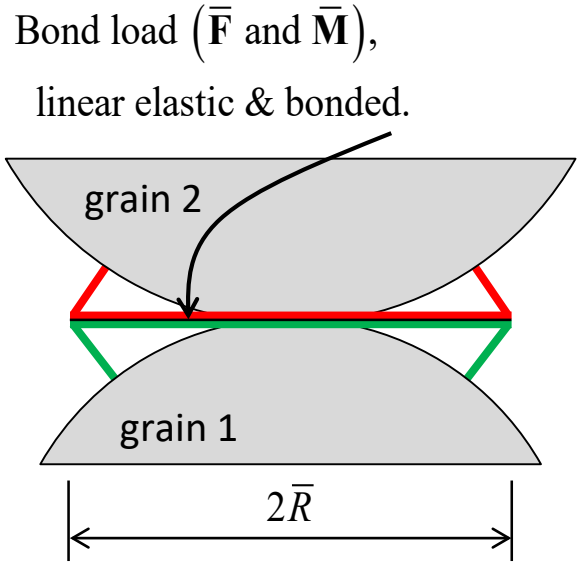
cutter (13-mm diameter)
depth of cut (1 mm)

Fracture & Flow (rock cutting)

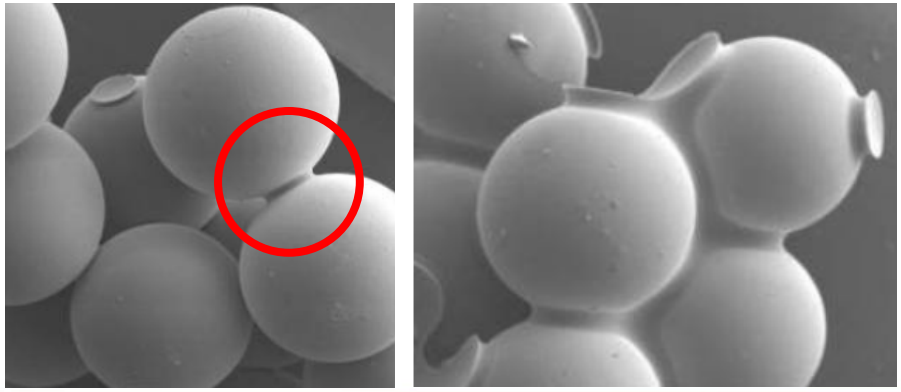
Rock Cutting (system behavior)

Models of rock-cutting tests (dry & wet)

- Create synthetic rock (parallel-bonded material).



Behaves like
glass beads
cemented with epoxy.

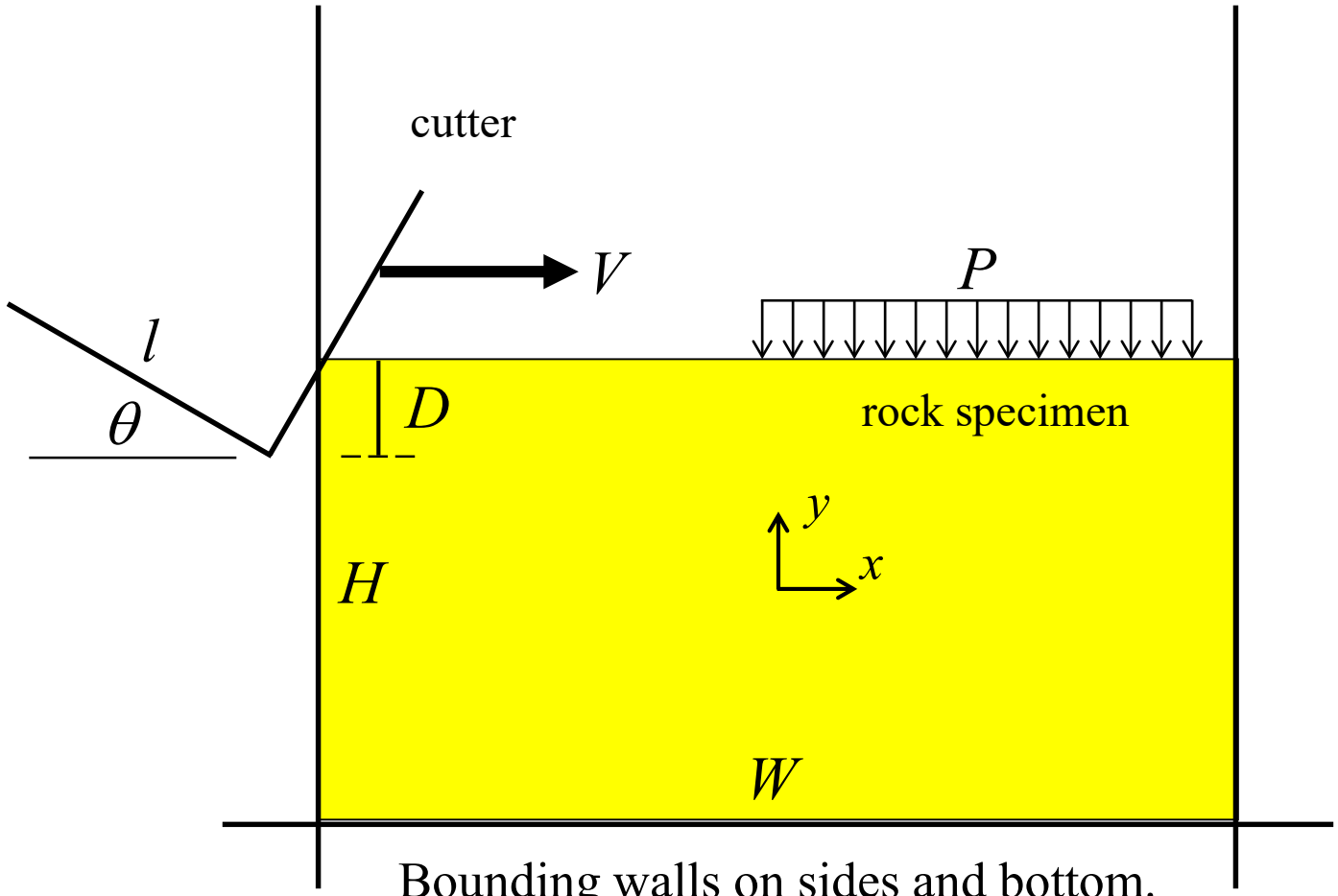


Rock Cutting (system behavior)

Models of rock-cutting tests (dry & wet)

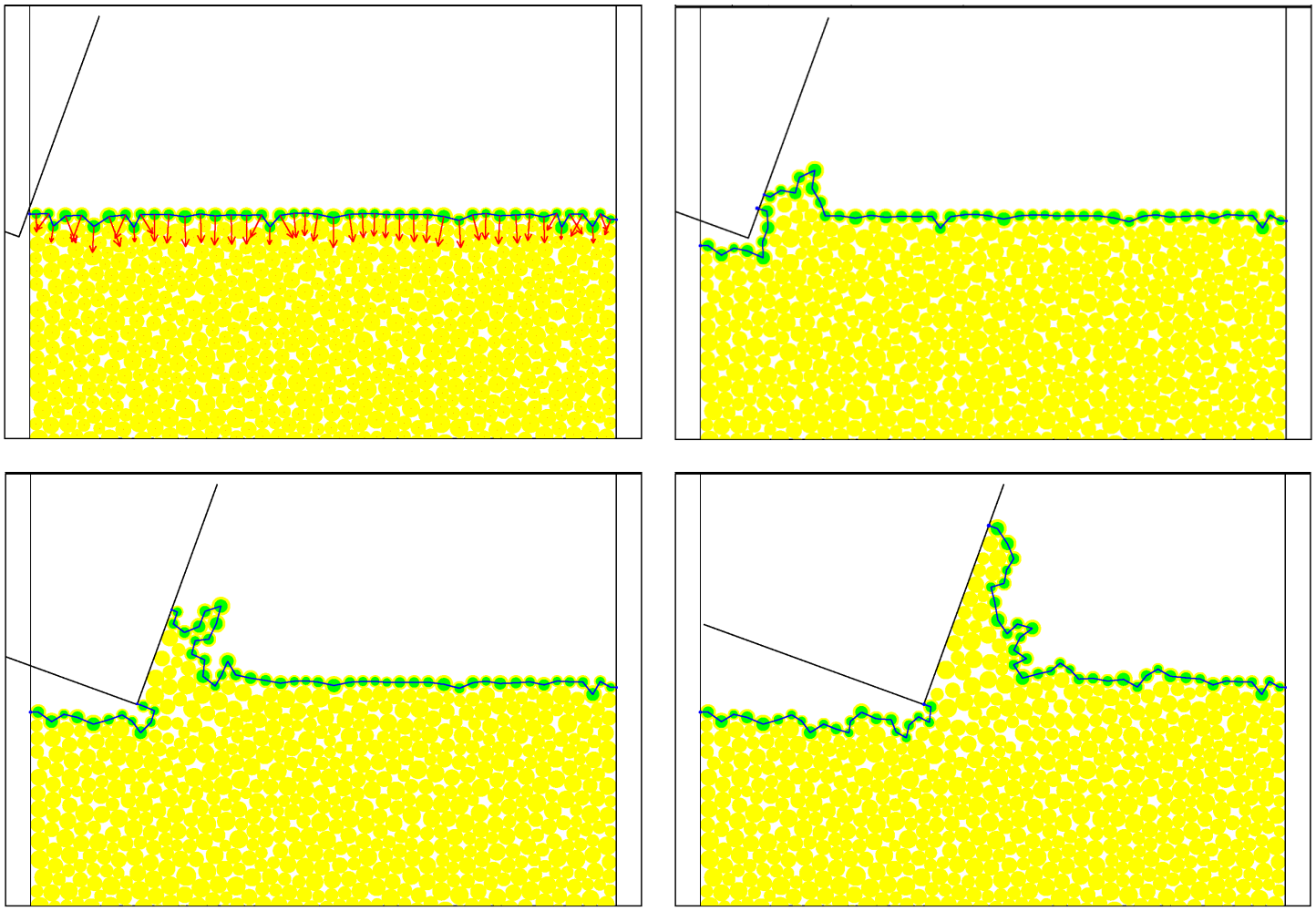
- Create synthetic rock (parallel-bonded material).
- Move cutter across surface of synthetic rock, while monitoring forces on the cutter & damage in the rock.
  - In a real borehole, drilling mud produces a pressure that acts on the rock surface and effectively strengthens the rock, thereby greatly increasing the energy requirements of drilling.
- Mimic the effect of drilling mud by identifying surface particles and applying pressure to those particles.
  - algorithms: chaining (2D) and shining-lamp (3D)
  - The pressure inhibits chip formation and leads to a more plastic-like zone of damage.

Rock Cutting (model, 2D)



Bounding walls on sides and bottom.
Pressure is applied to top rock surface.

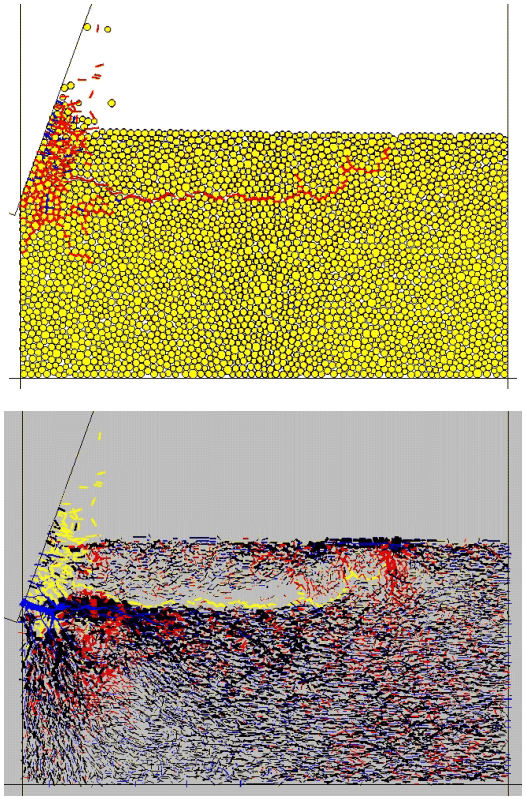
Rock Cutting (model, 2D)



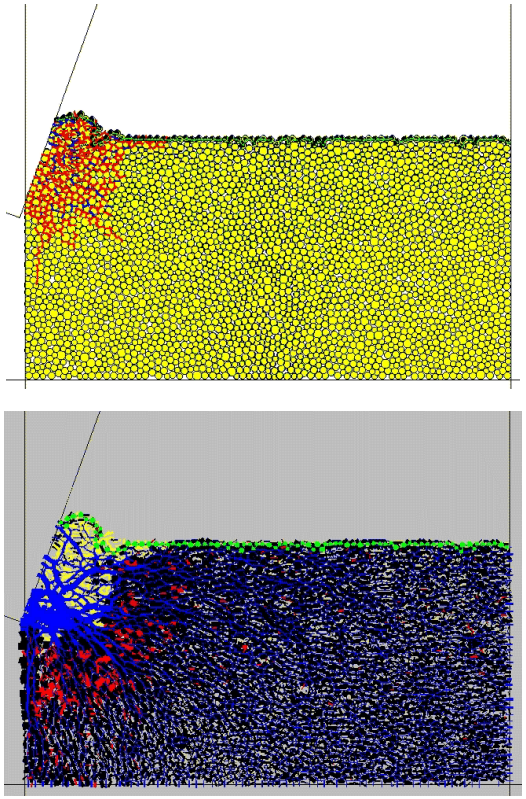
chaining algorithm

Rock Cutting (model, 2D)

initial period of damage formation



dry cutting



wet cutting
(5-MPa confining pressure)

■ damage ■

■ forces ■

PFC 4 *PFC* 6

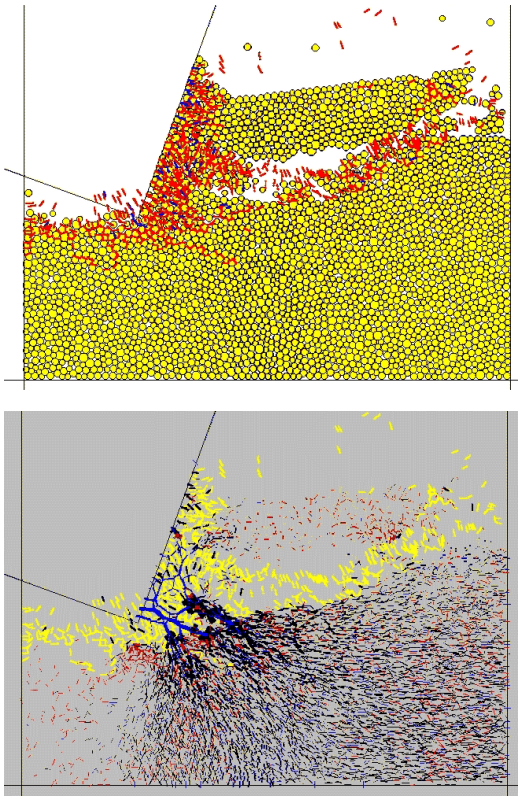
■ damage ■

■ forces ■

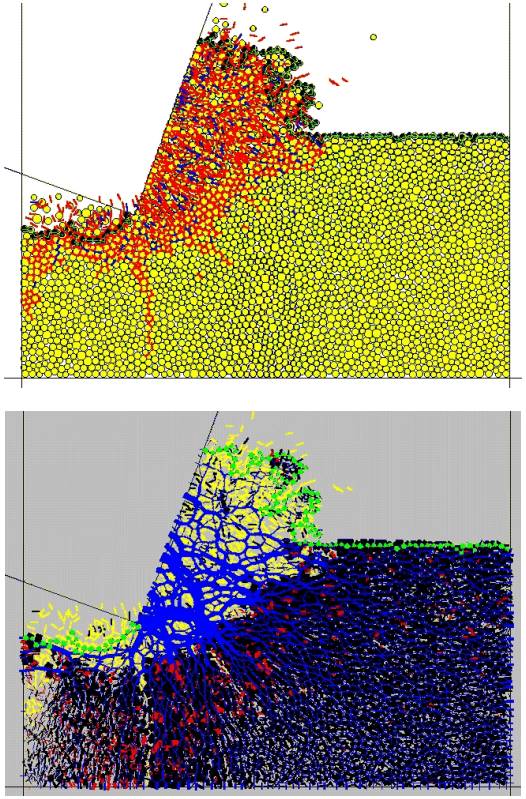
PFC 4 *PFC* 6

Rock Cutting (model, 2D)

steady-state condition



dry cutting



wet cutting
(5-MPa confining pressure)

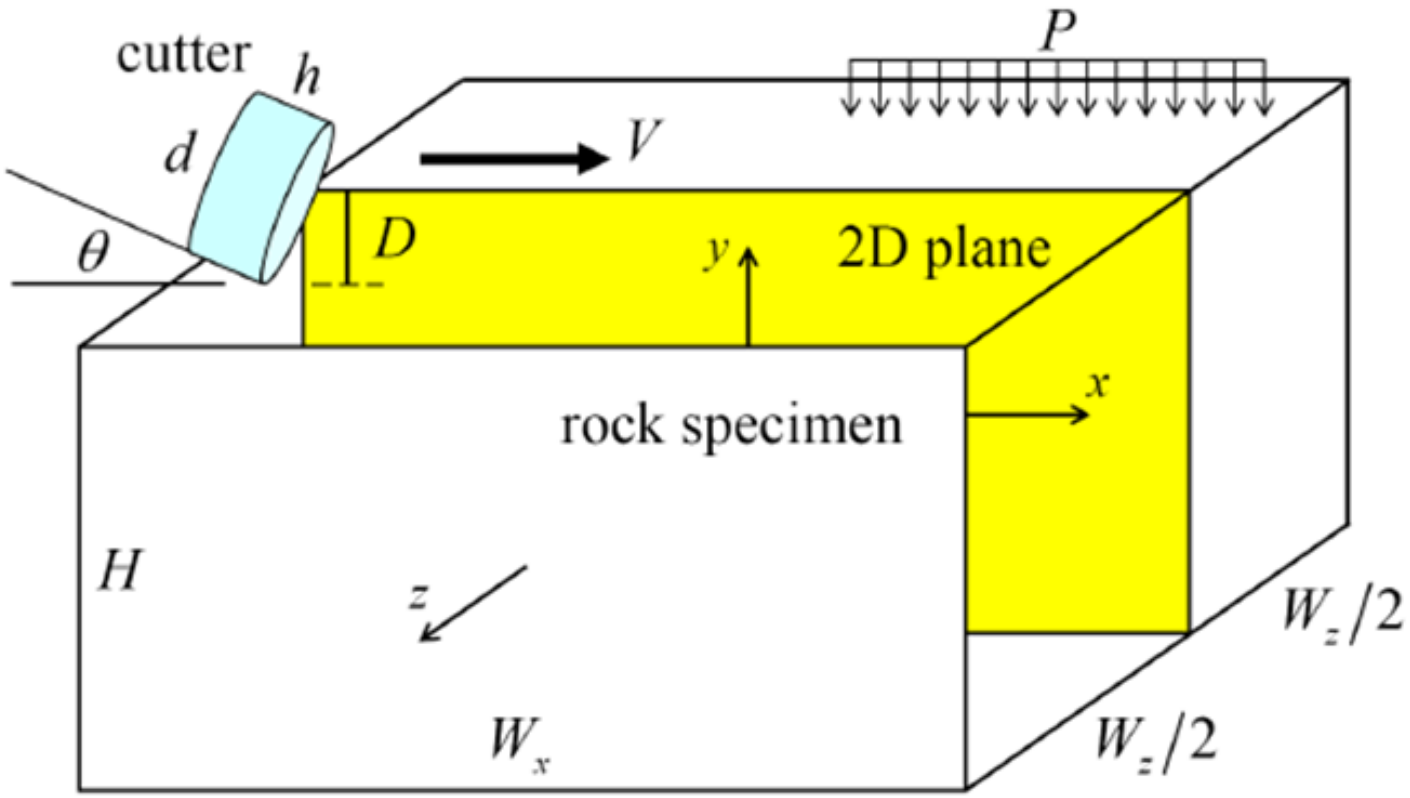
■ damage ■

■ forces ■

■ damage ■

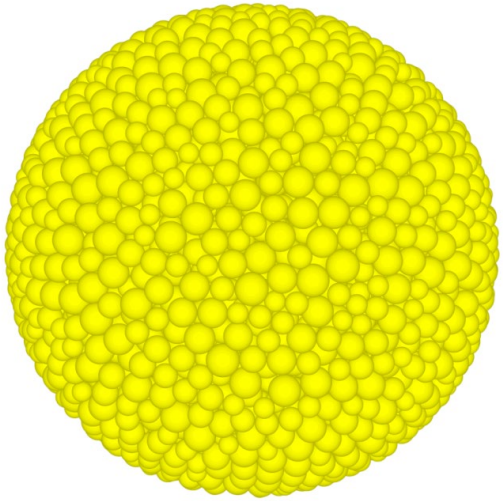
■ forces ■

Rock Cutting (model, 3D)

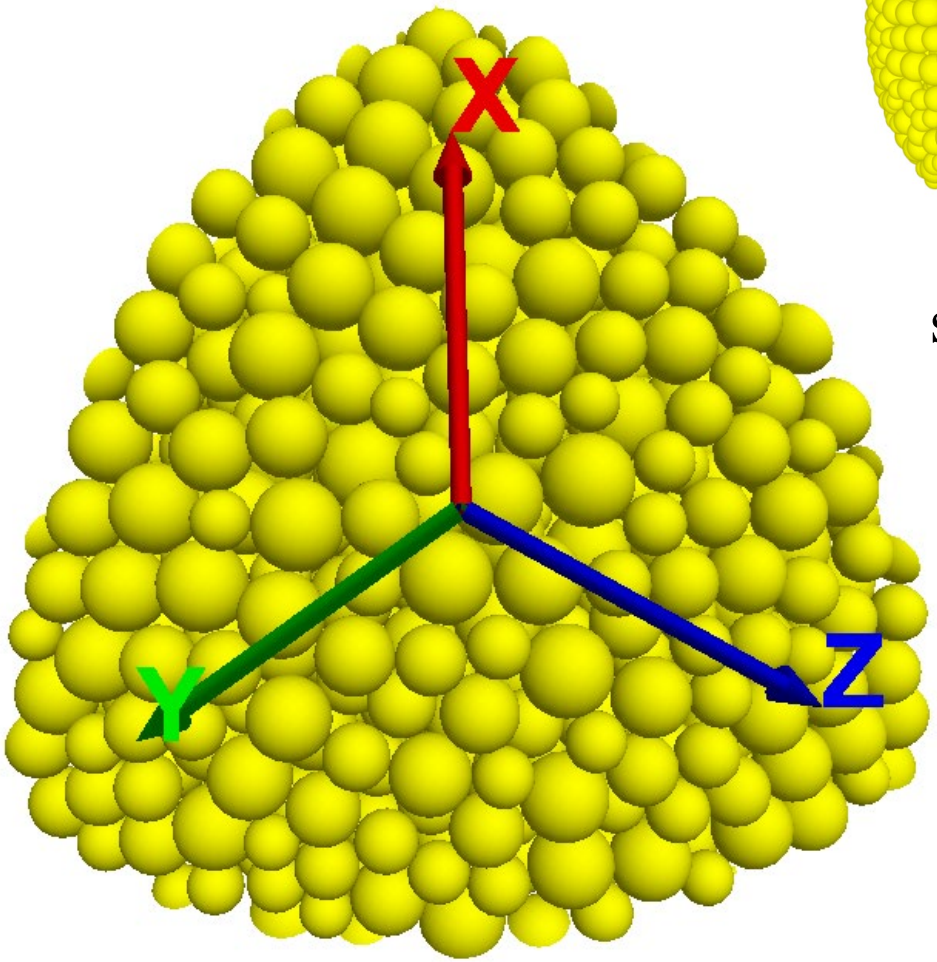


Bounding walls on sides and bottom.
Pressure is applied to entire rock surface.

Rock Cutting (model, 3D)



synthetic rock



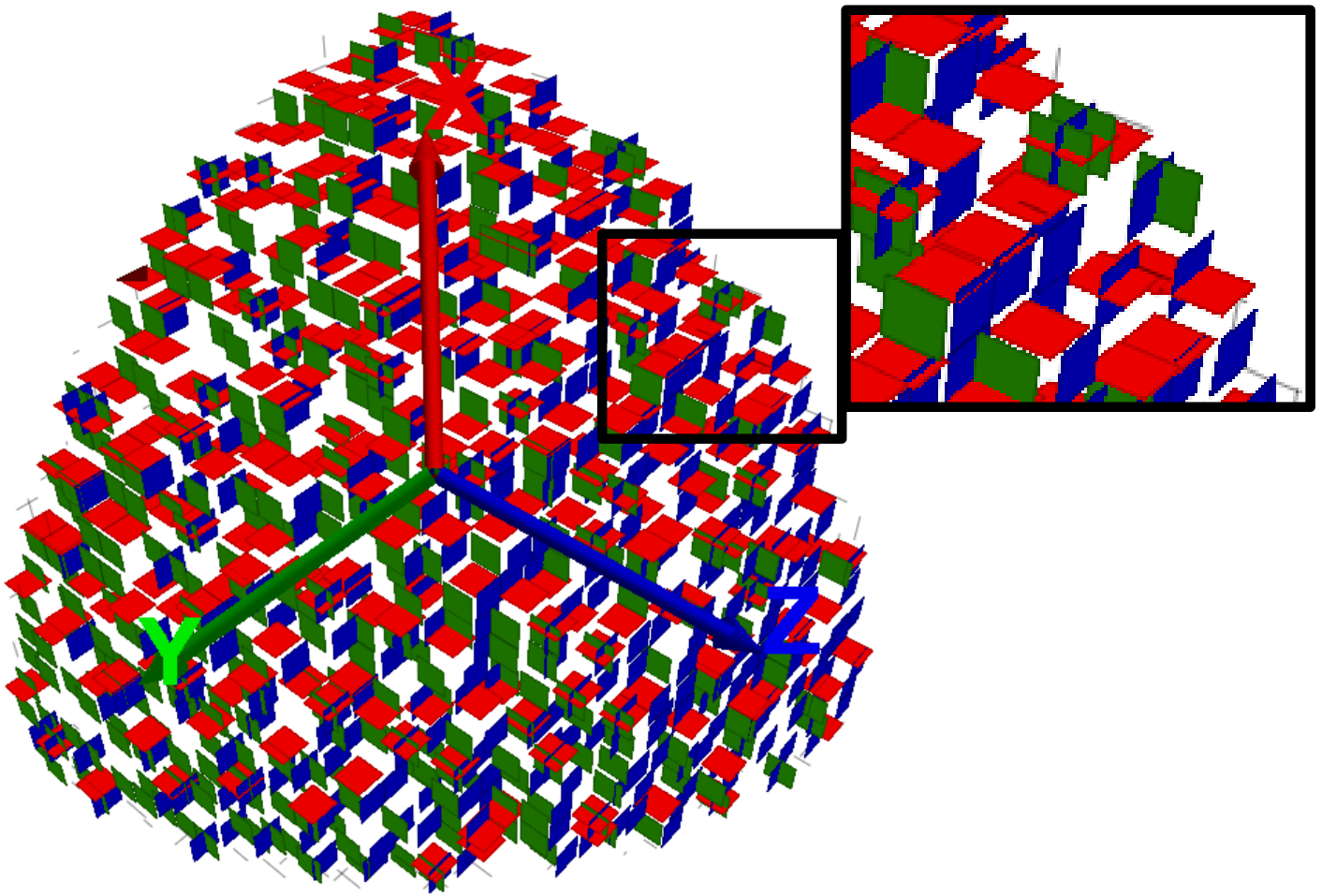
shining-lamp algorithm

Potyondy, D. (2012) "*PFC3D* Pressure Boundary Condition," Itasca Consulting Group, Inc., Technical Memorandum ICG7233-L (January 30, 2012), Minneapolis, Minnesota.

Rock Cutting (model, 3D)

grid-cell intersections

(ratio of cell-size to average particle diameter: **1/2**)

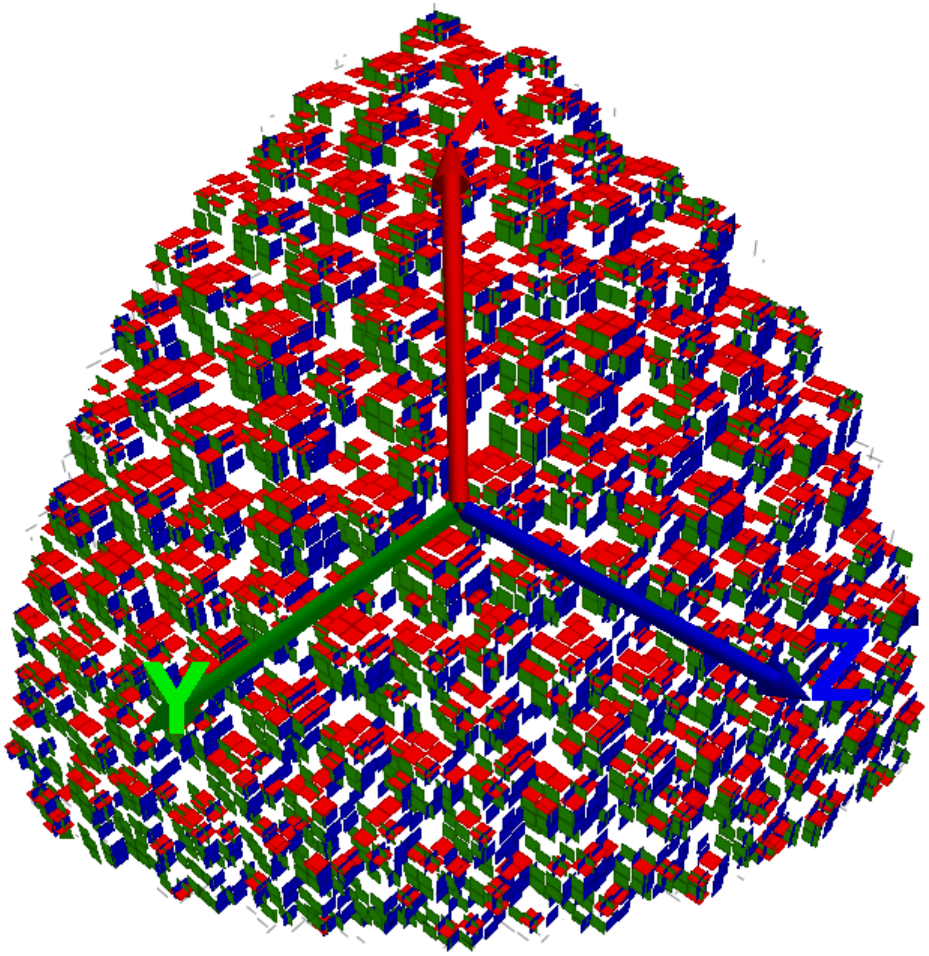


shining-lamp algorithm

Rock Cutting (model, 3D)

grid-cell intersections

(ratio of cell-size to average particle diameter: **1/4**)

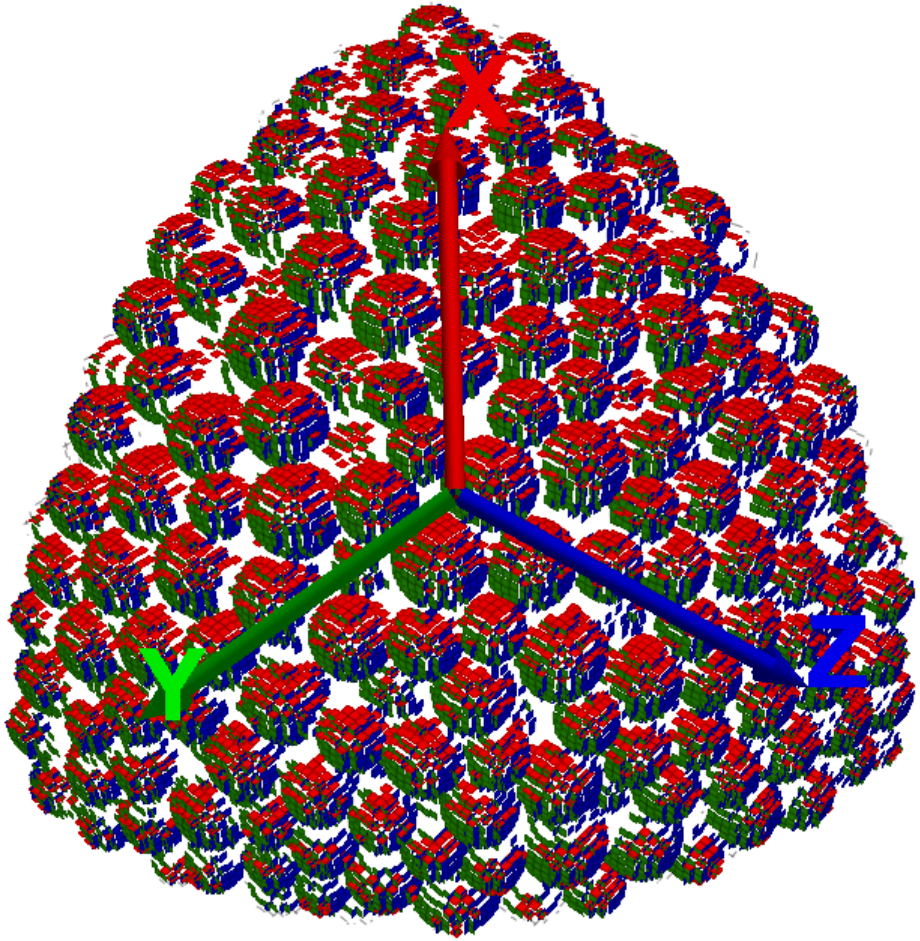


shining-lamp algorithm

Rock Cutting (model, 3D)

grid-cell intersections

(ratio of cell-size to average particle diameter: **1/8**)

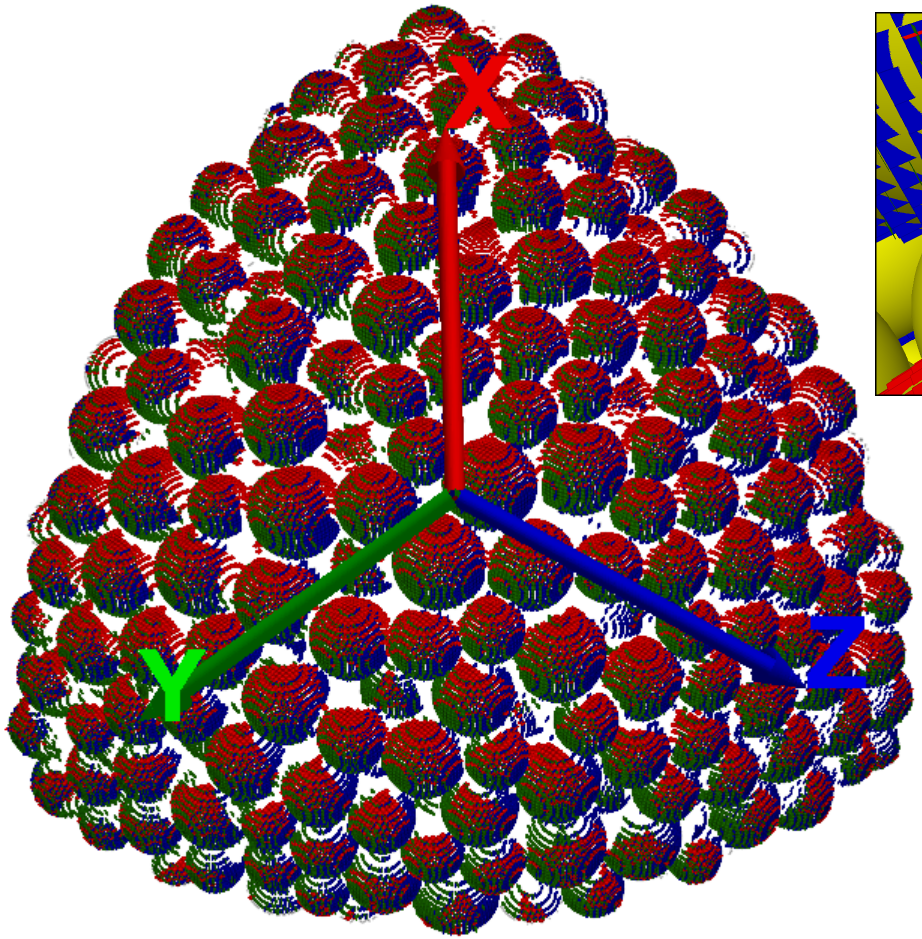


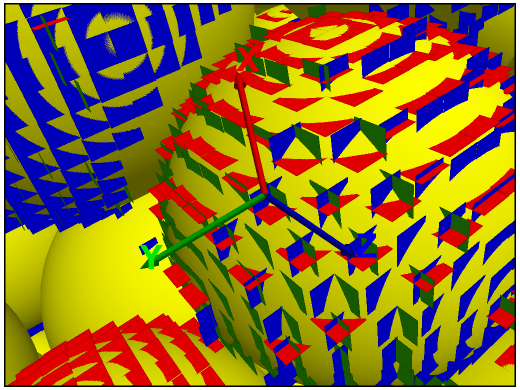
shining-lamp algorithm

Rock Cutting (model, 3D)

grid-cell intersections

(ratio of cell-size to average particle diameter: **1/16**)



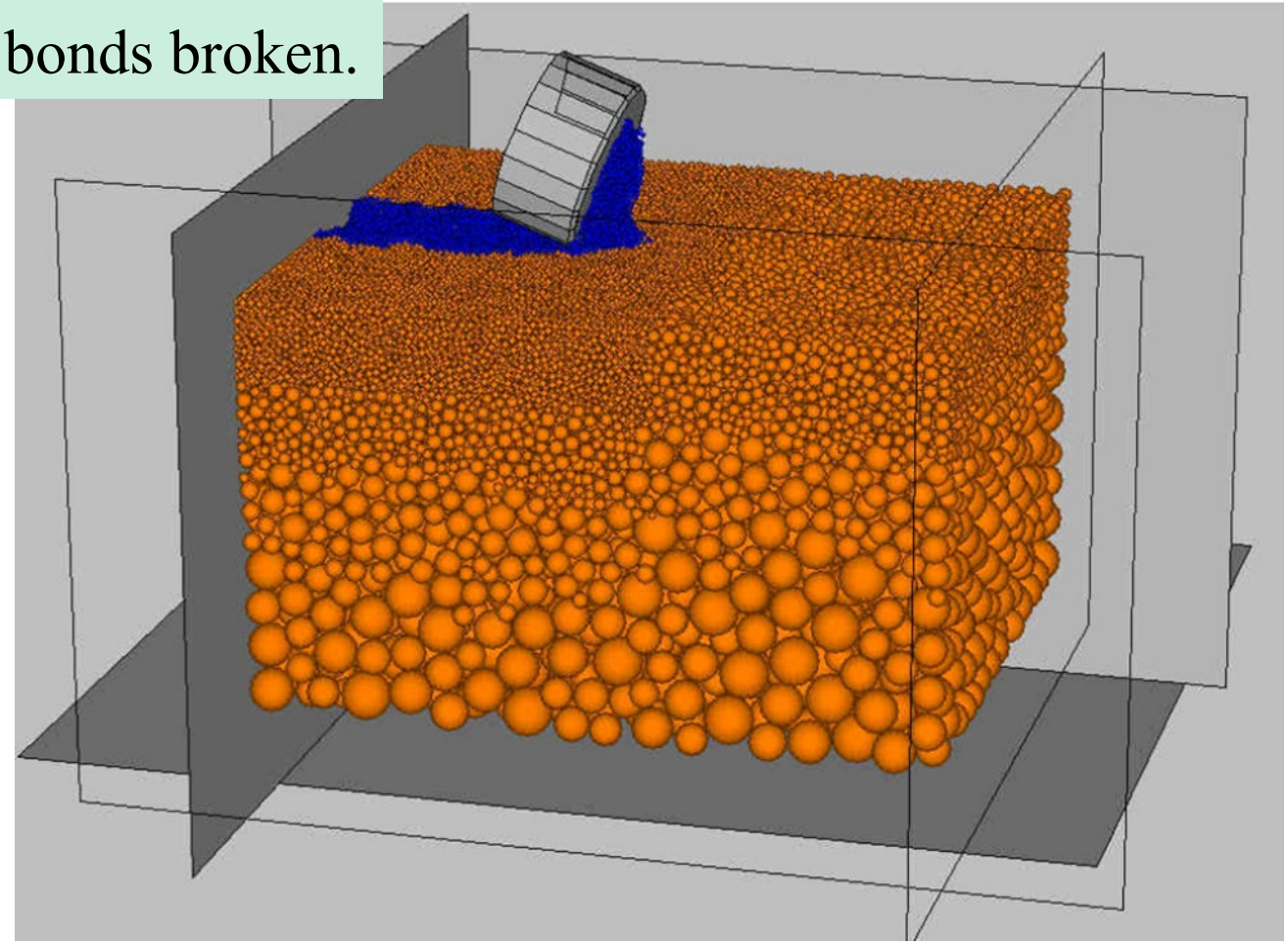


shining-lamp algorithm

Rock Cutting (model, 3D)

wet cutting
(20-MPa confining pressure)

Blue particles have had all of their bonds broken.



Ledgerwood, L.W. (2013) "*PFC3D* Modeling of Rock Cutting under Pressure Calibrated to the Inelastic Region of Triaxial Tests at High Strain," extended abstract in Proc. 6th Int. Conf. on Discrete Element Methods (DEM6), Colorado, USA, 5-6 August 2013.

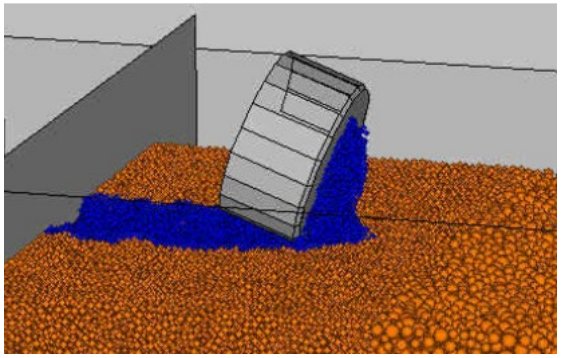
Rock Cutting (mechanisms controlling system behavior)

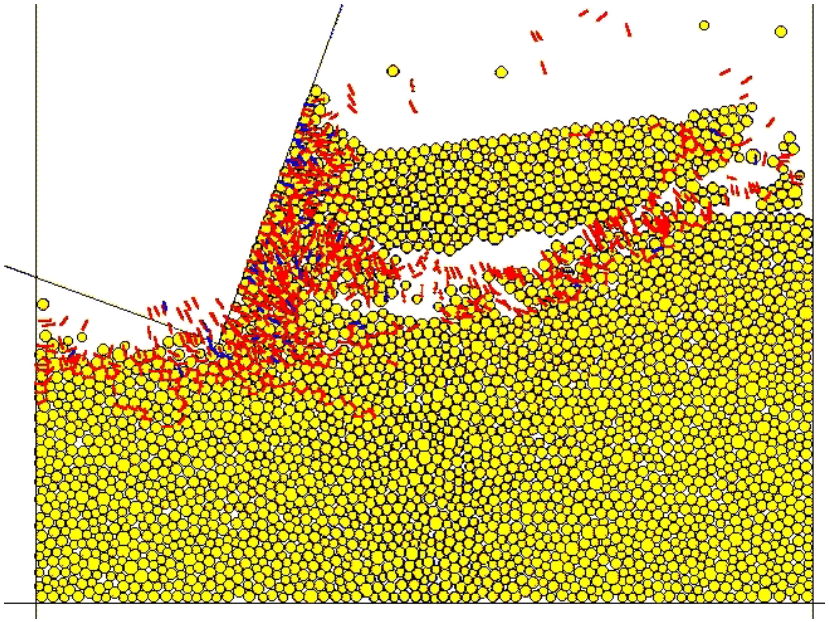
After an initial period of damage formation, the cutter-rock system reaches a steady-state condition in which the cutter is no longer in contact with virgin rock, but instead is bearing against broken material.

The damaged region consists of broken material that extends in front of and slightly below the cutter, and the broken material flows beneath the cutter.

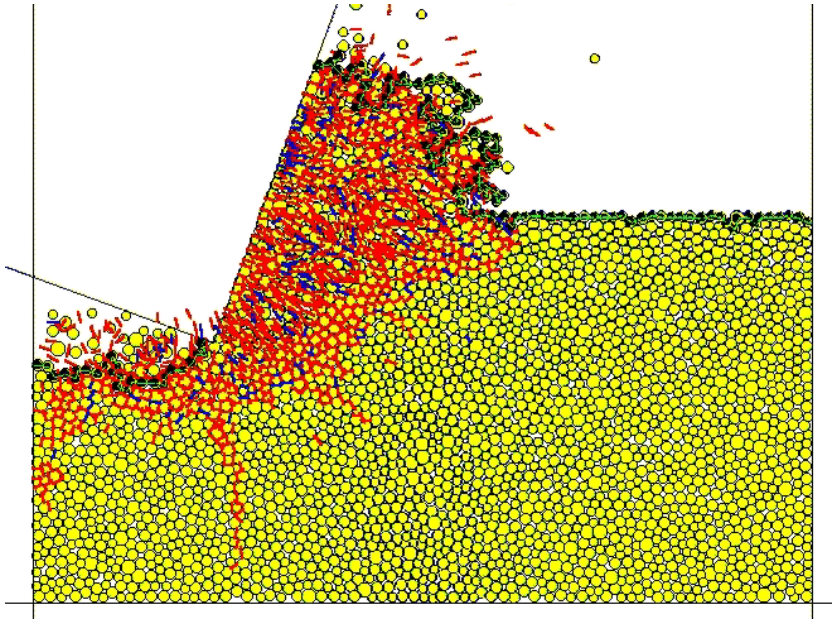
Rock Cutting (mechanisms controlling system behavior)

Damaged region differs for dry & wet cutting.





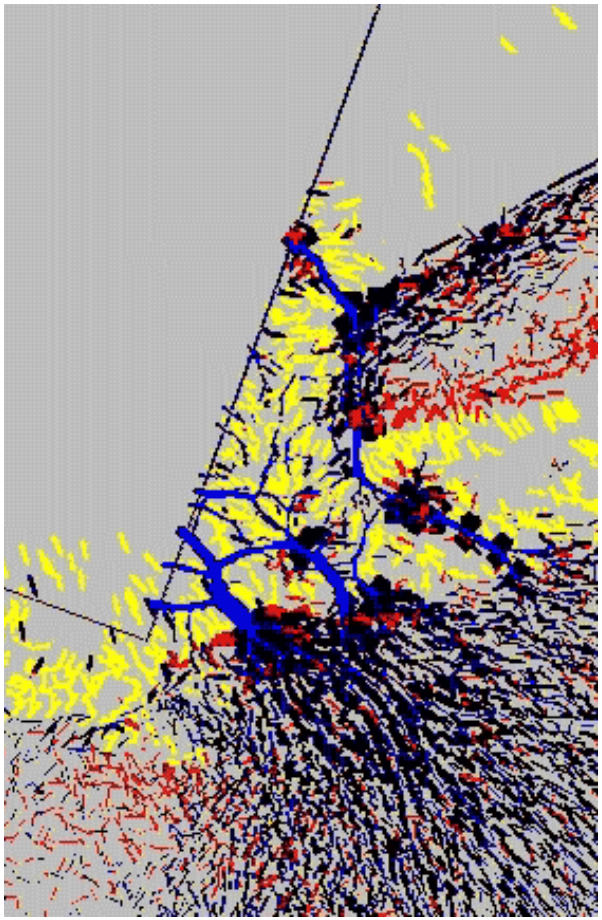
dry cutting
large fragments



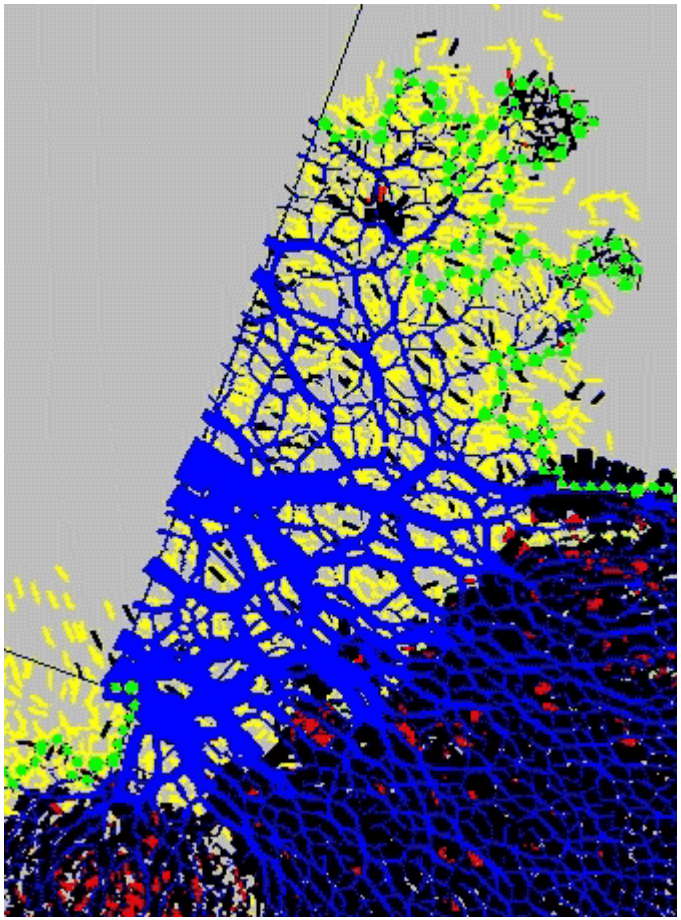
wet cutting
broken material extrudes up face

Rock Cutting (mechanisms controlling system behavior)

Forces flow through broken material into virgin rock.



- dry cut, forces

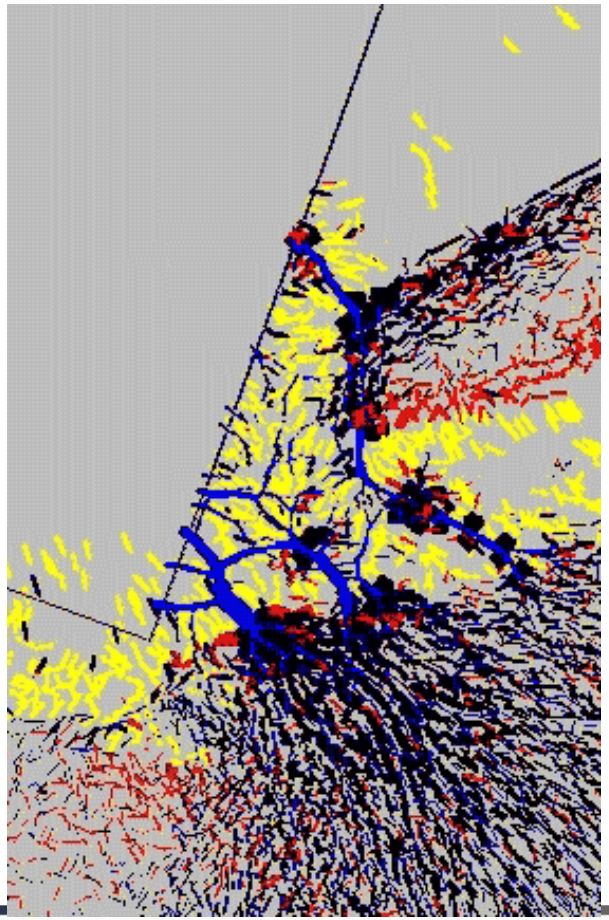


- wet cut, forces

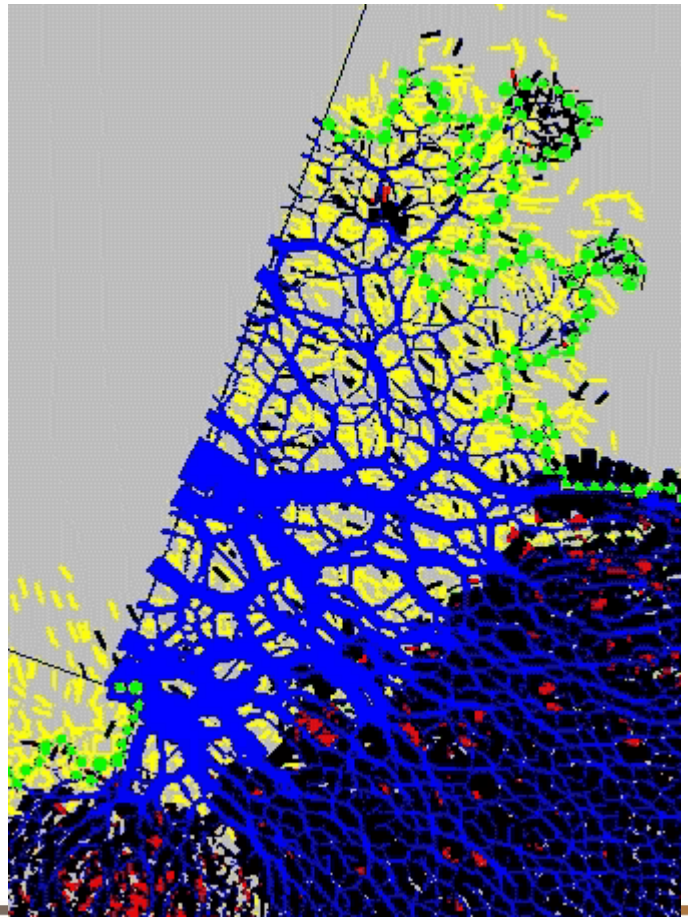
Rock Cutting (mechanisms controlling system behavior)

Mechanical response of cutter-rock system is controlled by:

- properties of rock on periphery of damaged region
- properties of broken material as it flows beneath the cutter

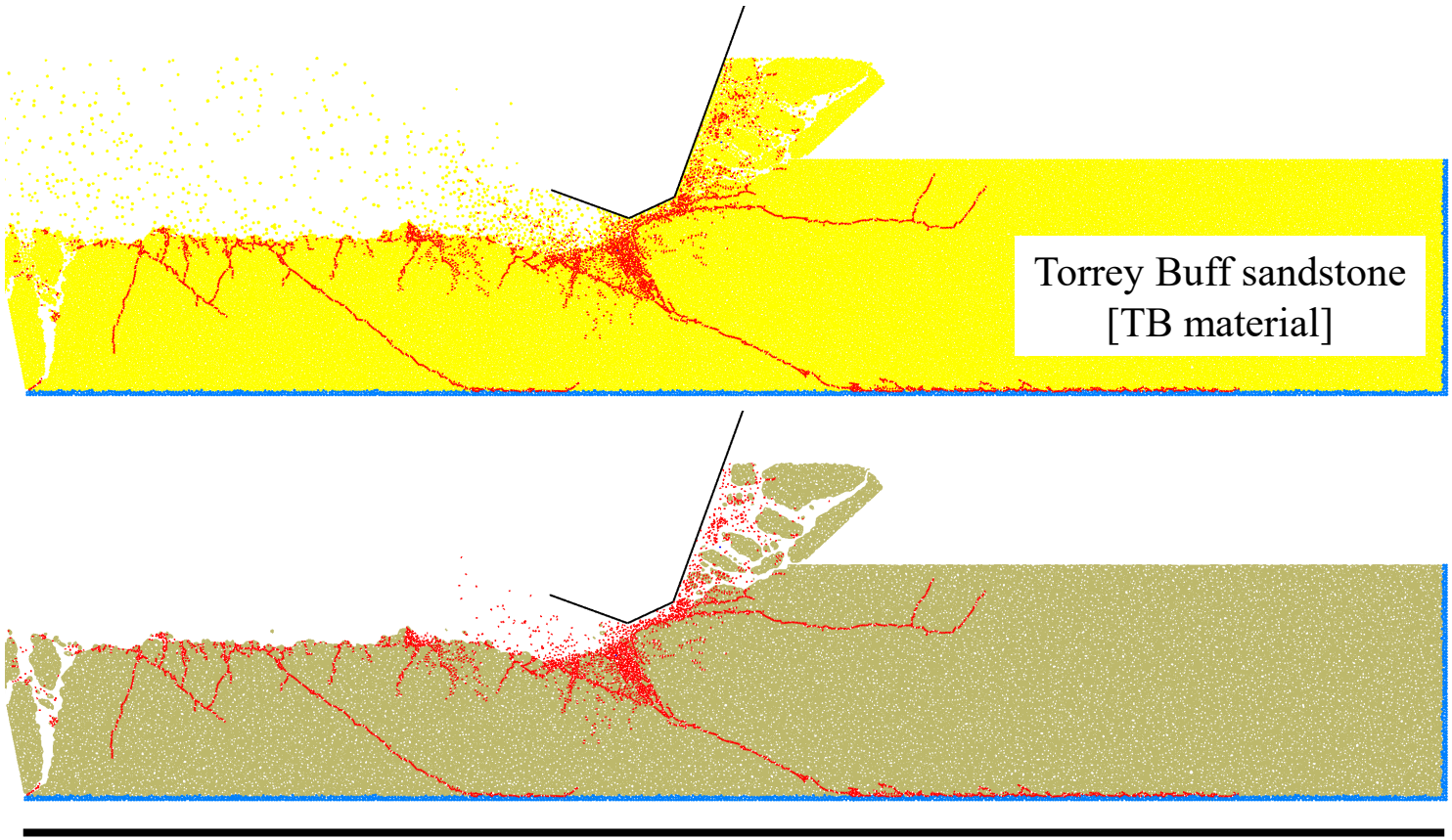


■ dry cut, forces



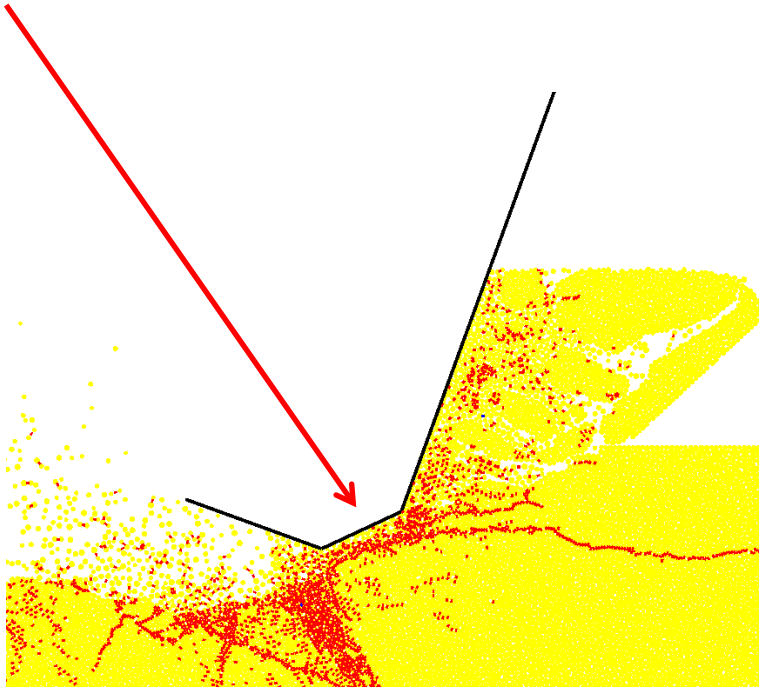
■ wet cut, forces

Rock Cutting (quantitative evaluation of 2D dry cutting)



Rock Cutting (quantitative evaluation of 2D dry cutting)

The previous mechanisms occur at the grain scale. Bonded-particle model must have grain size similar to that of rock grains, or at least sufficient to resolve cutter chamfer.



Rock Cutting (quantitative evaluation of 2D dry cutting)

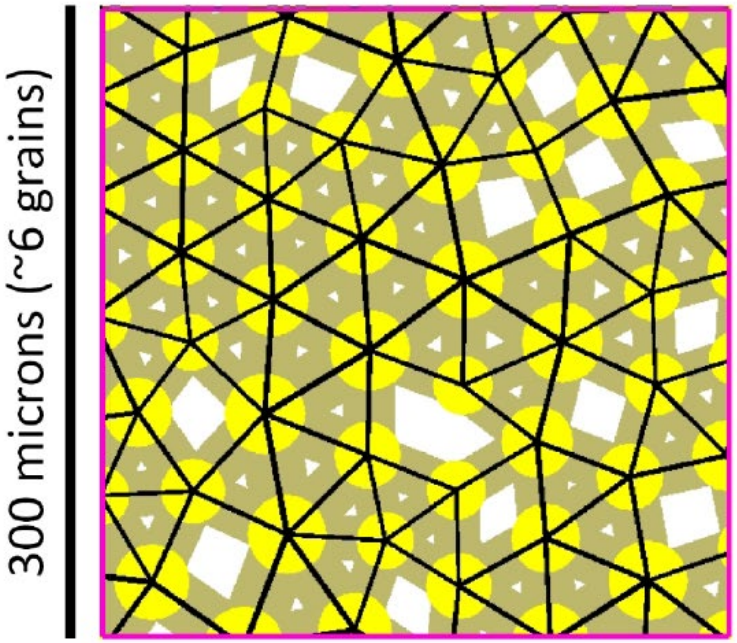
The previous mechanisms occur at the grain scale. Bonded-particle model must have grain size similar to that of rock grains, or at least sufficient to resolve cutter chamfer.

What is grain size, and grain microstructure of Torrey Buff sandstone? This information will inform model creation.

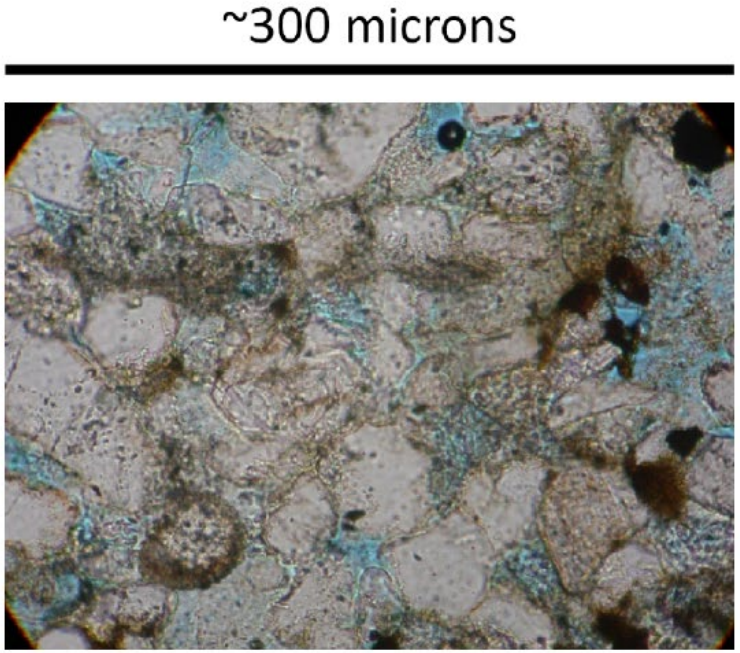
Rock Cutting (quantitative evaluation of 2D dry cutting)

Microstructural features of TB material & Torrey Buff sandstone.

Grain size is 50 microns



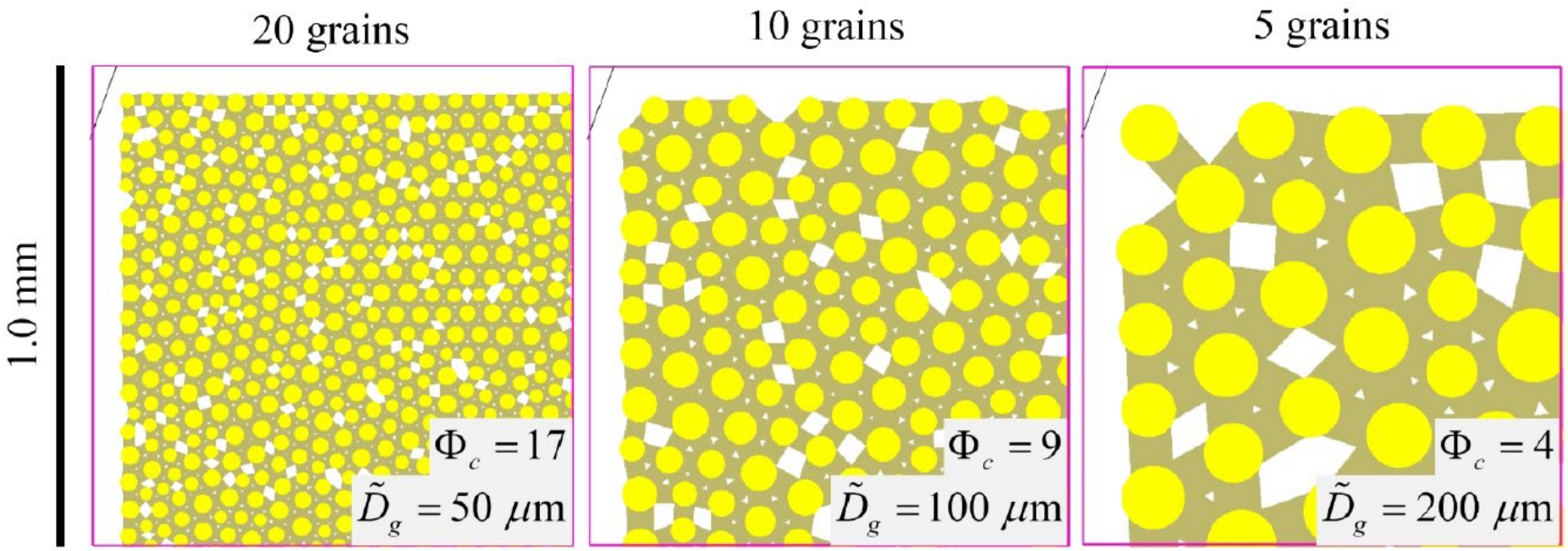
grains (yellow, 80% of true size)
cement (tan, 50% of true size)



Mostly quartz.
Pores highlighted by blue epoxy.

Rock Cutting (quantitative evaluation of 2D dry cutting)

Construct three TB materials that differ only in their grain size.



Φ_c is cutter resolution (number of grains across chamfer width)

Rock Cutting (quantitative evaluation of 2D dry cutting)

Microstructure of TB material is simplification of true microstructure; therefore, microproperties chosen via calibration process, attempting to match:

- Tensile strength
- Compressive strengths (at 0, 3 and 10 MPa)

Rock Cutting (quantitative evaluation of 2D dry cutting)

Microstructure of TB material is simplification of true microstructure; therefore, microproperties chosen via calibration process, attempting to match:

- Tensile strength
- Compressive strengths (at 0, 3 and 10 MPa)

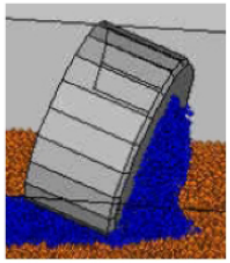
TB materials (all grains sizes):

- **match** tensile strength, Young's modulus and Poisson's ratio of Torrey Buff sandstone
- **underestimate** the compressive strengths

We do not expect a quantitative match to forces in the 2D rock-cut test, because. . .

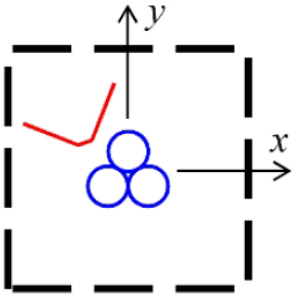
Rock Cutting (quantitative evaluation of 2D dry cutting)

The 2D synthetic cutter is not cutting a groove, but instead is cutting a slice completely across a unit-thickness rock specimen.



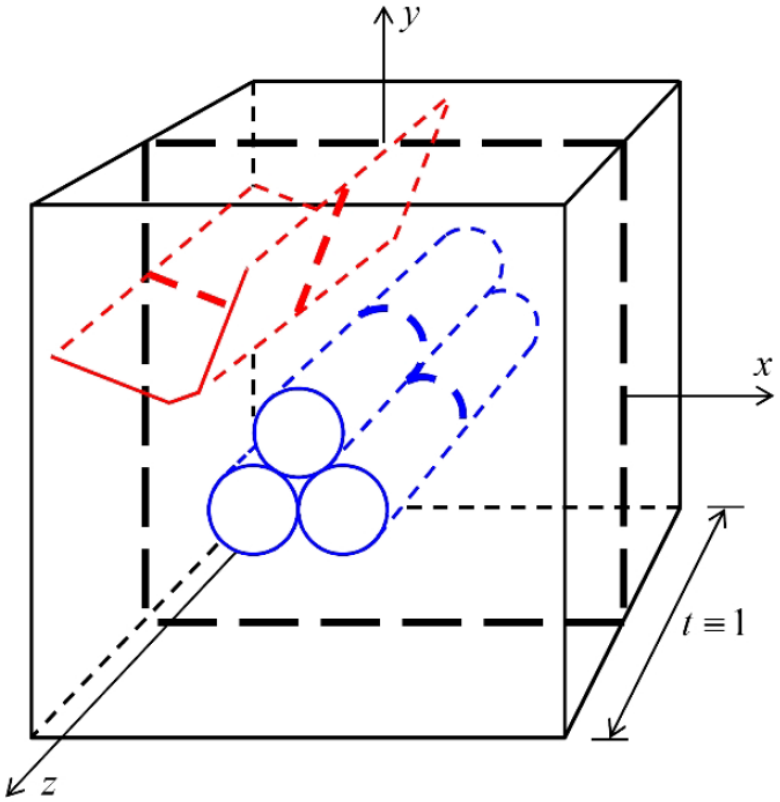
spherical particles (rock)
and faceted walls (cutter)

3D model



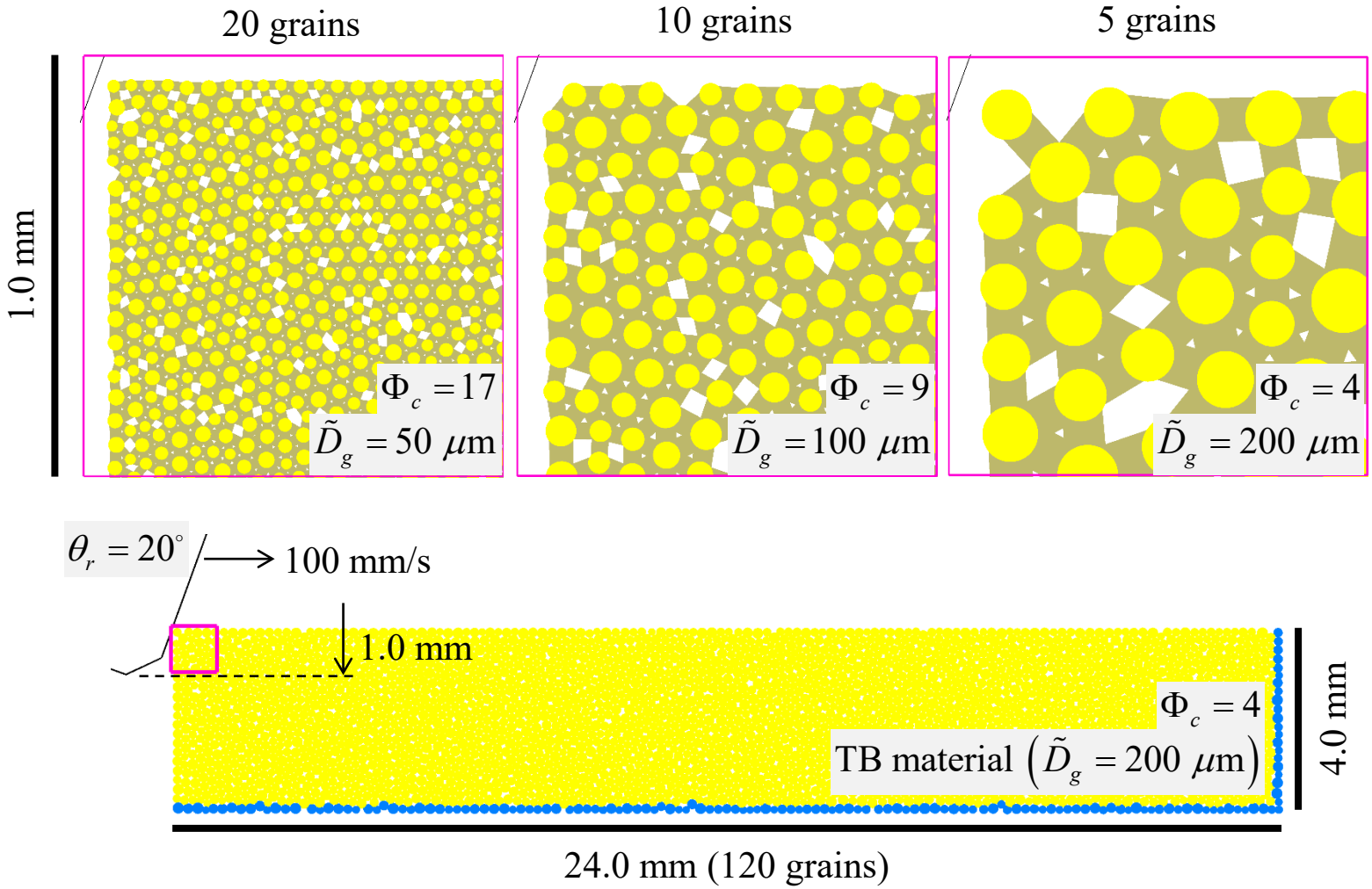
unit-thickness disks (rock)
and segmented walls (cutter)

2D model



Rock Cutting (quantitative evaluation of 2D dry cutting)

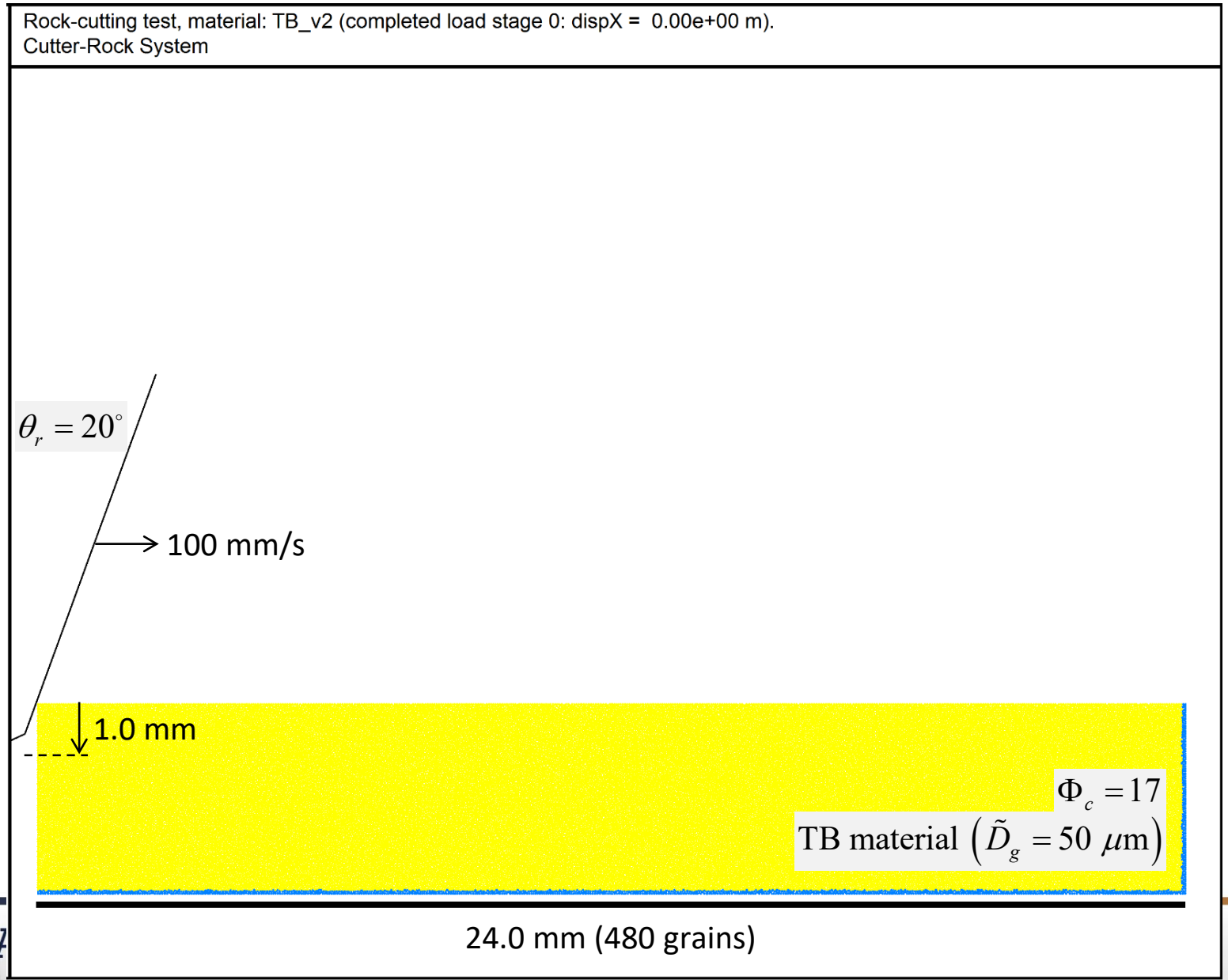
We simulated the following 2D dry rock-cut test:



Rock Cutting (quantitative evaluation of 2D dry cutting)

The rock-cut test behavior for the TB material with a grain size equal to that of Torrey Buff sandstone is shown on the following 10 slides.

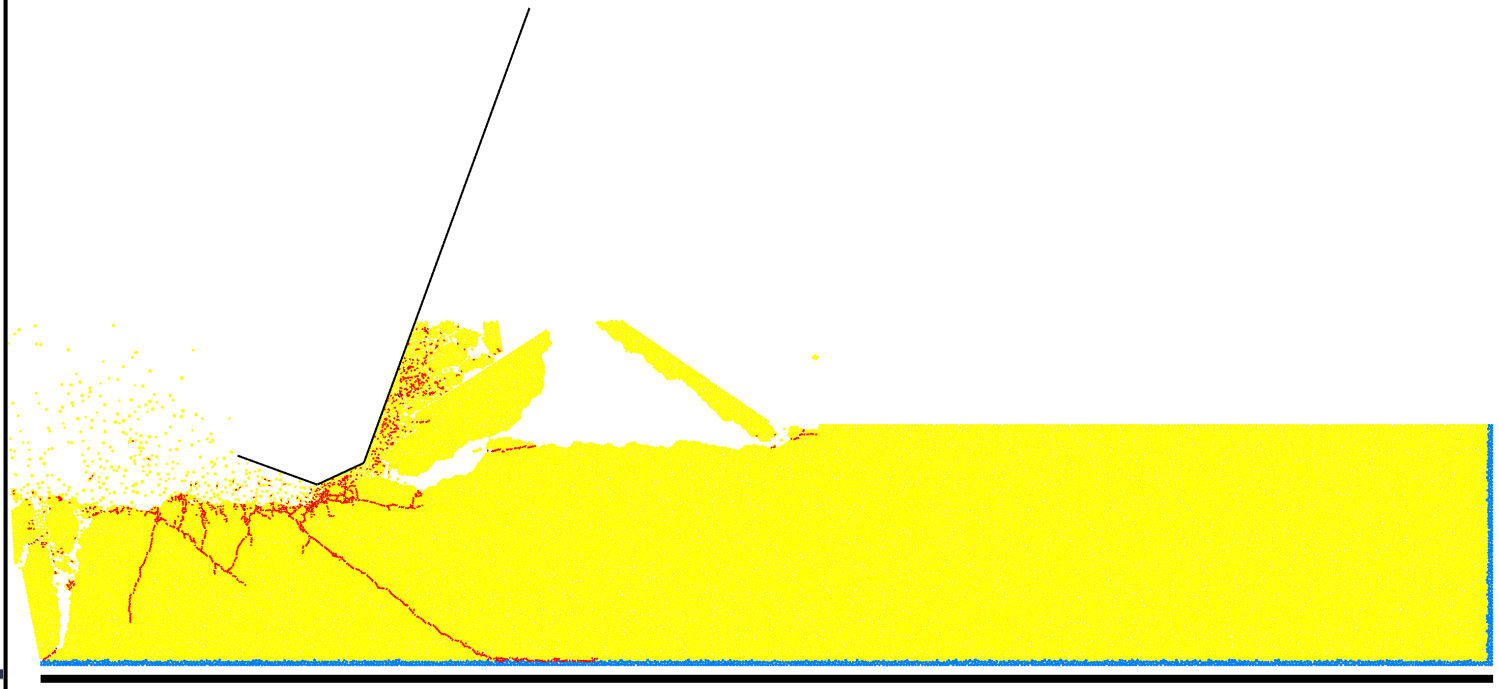
Rock Cutting (quantitative evaluation of 2D dry cutting)



Rock Cutting (quantitative evaluation of 2D dry cutting)

Rock-cutting test, material: TB_v2 (completed load stage 112: dispX = 5.60e-03 m).
Cutter-Rock System

Filtered cracks with gap less than 50 microns (red), and grains (yellow)

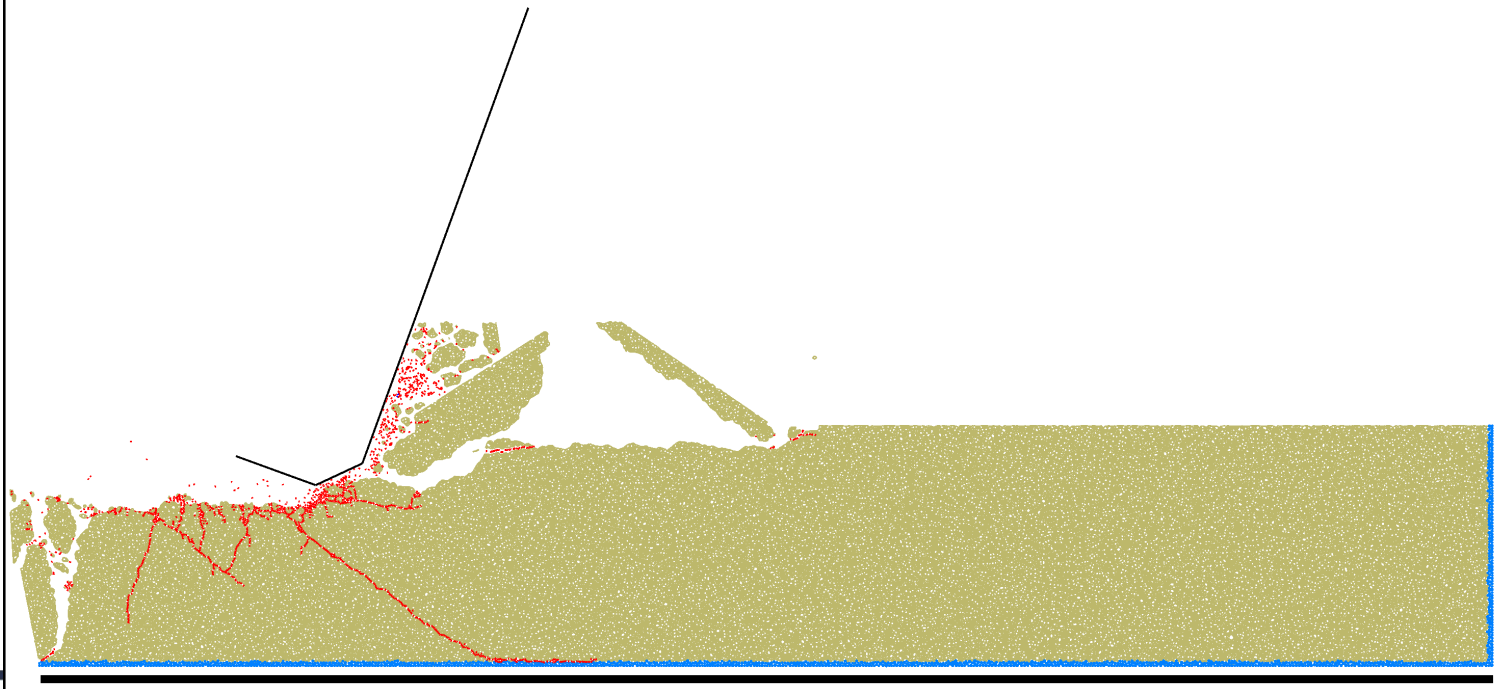


24.0 mm (480 grains)

Rock Cutting (quantitative evaluation of 2D dry cutting)

Rock-cutting test, material: TB_v2 (completed load stage 112: dispX = 5.60e-03 m).
Cutter-Rock System

Filtered cracks with gap less than 50 microns (red), and intact bonds (cement, tan)

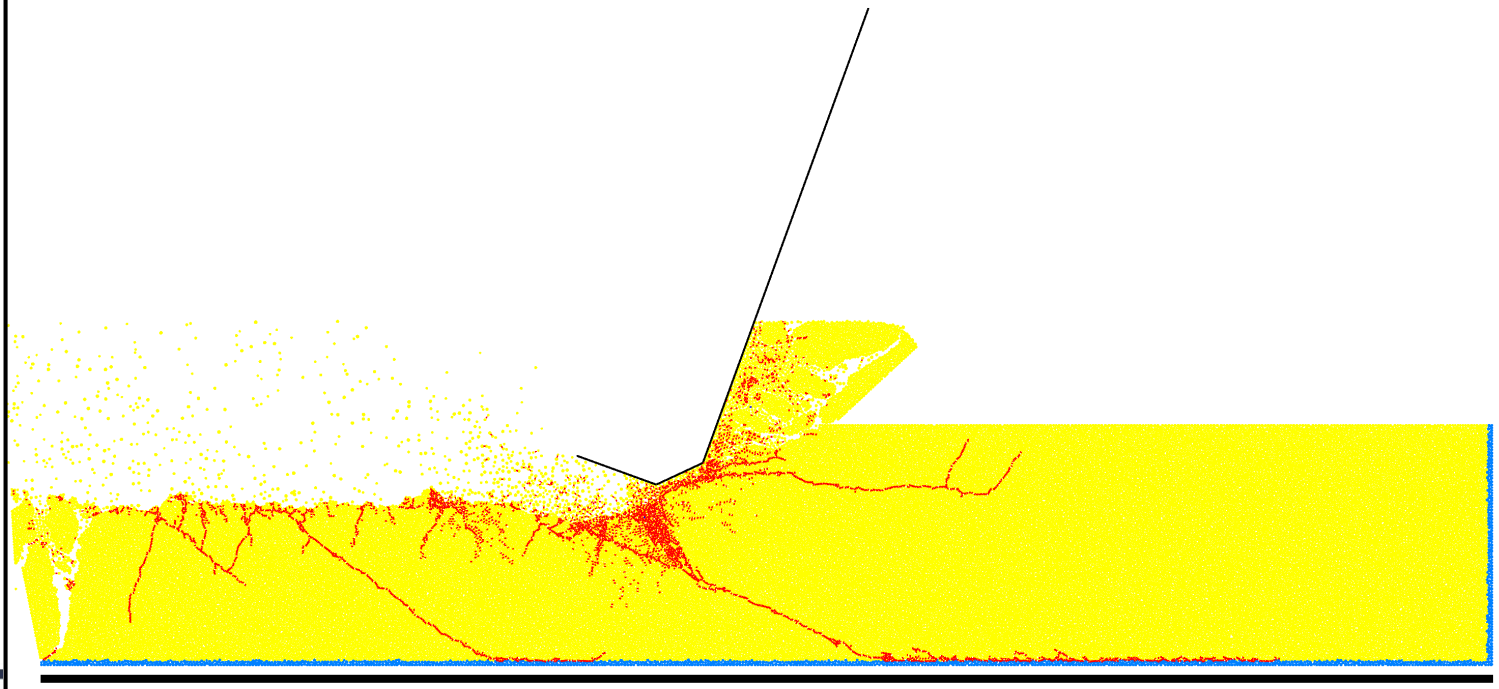


24.0 mm (480 grains)

Rock Cutting (quantitative evaluation of 2D dry cutting)

Rock-cutting test, material: TB_v2 (completed load stage 224: dispX = 1.12e-02 m).
Cutter-Rock System

Filtered cracks with gap less than 50 microns (red), and grains (yellow)

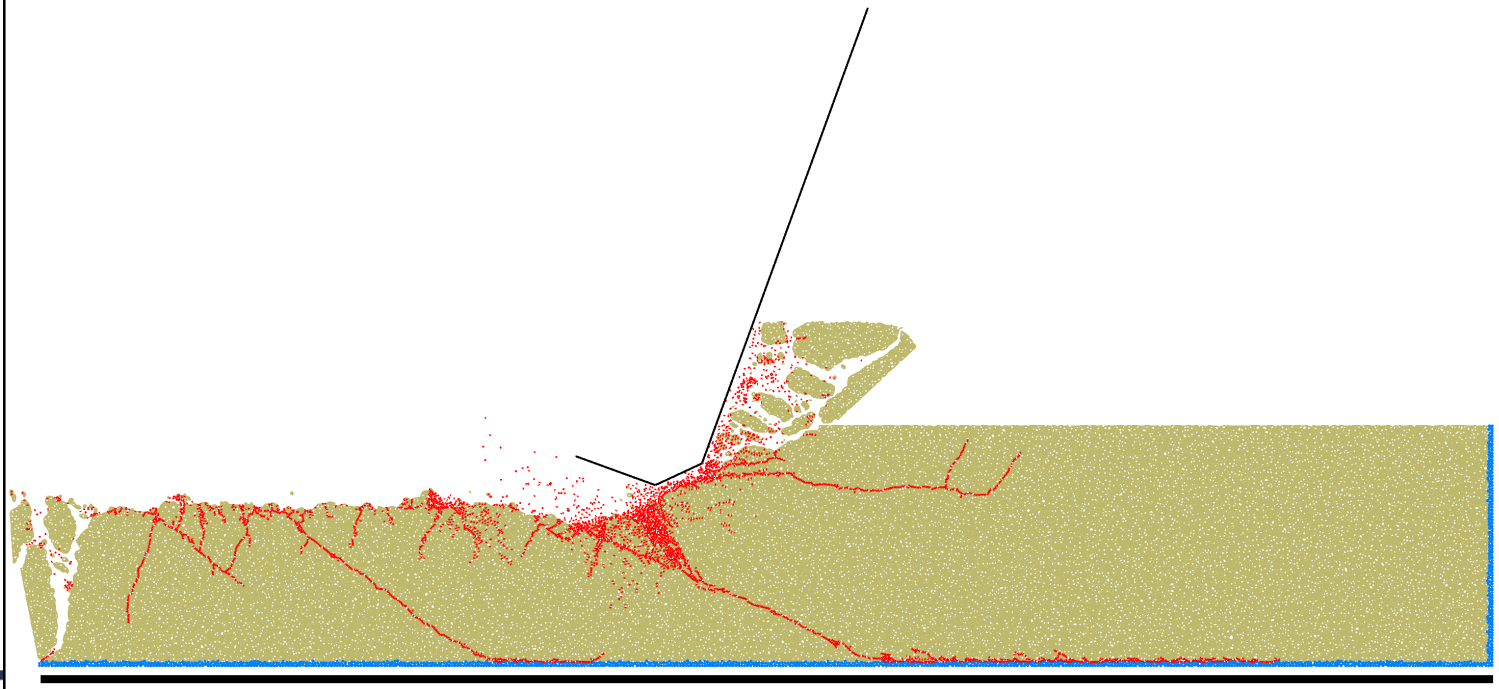


24.0 mm (480 grains)

Rock Cutting (quantitative evaluation of 2D dry cutting)

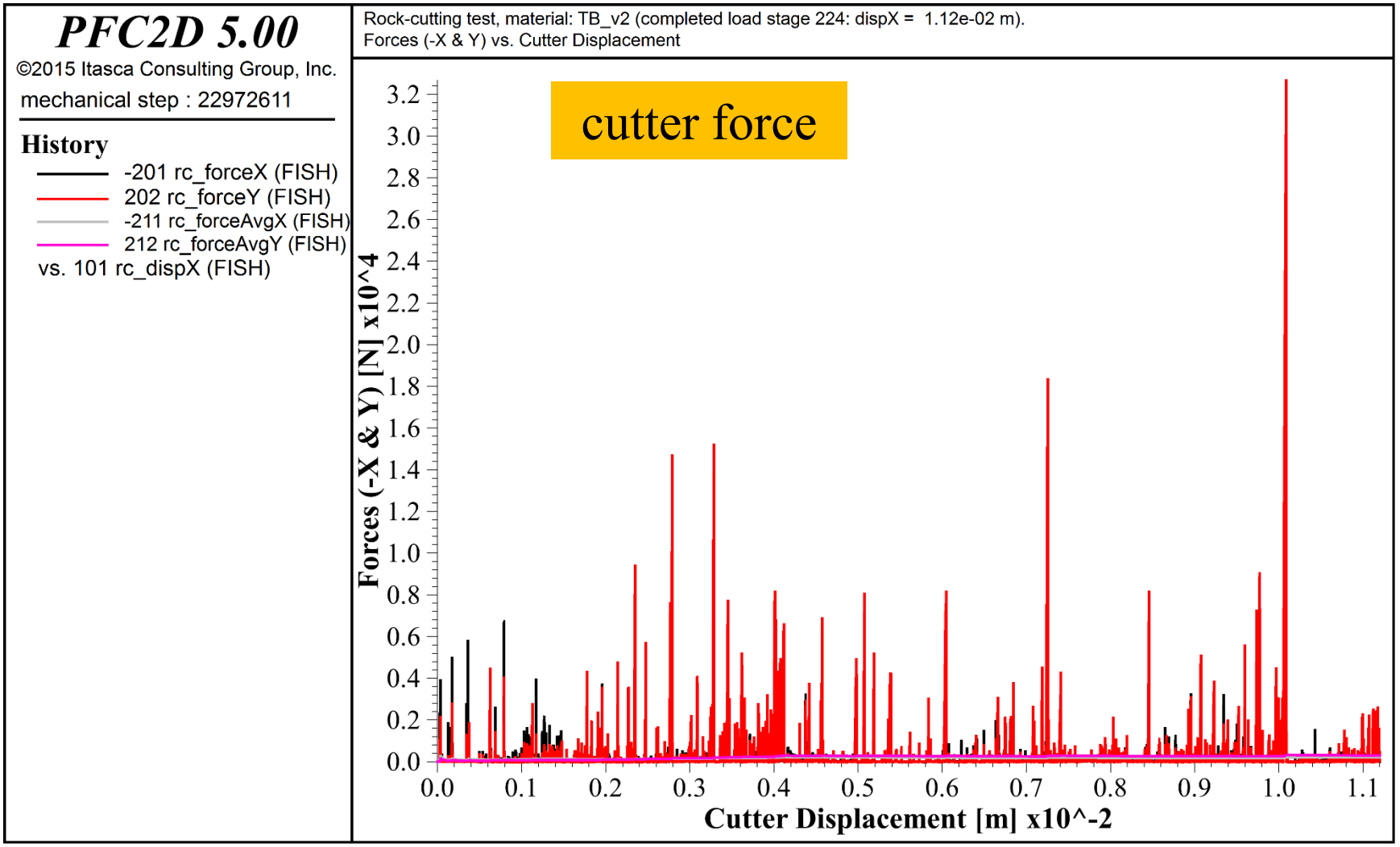
Rock-cutting test, material: TB_v2 (completed load stage 224: dispX = 1.12e-02 m).
Cutter-Rock System

Filtered cracks with gap less than 50 microns (red), and intact bonds (cement, tan)

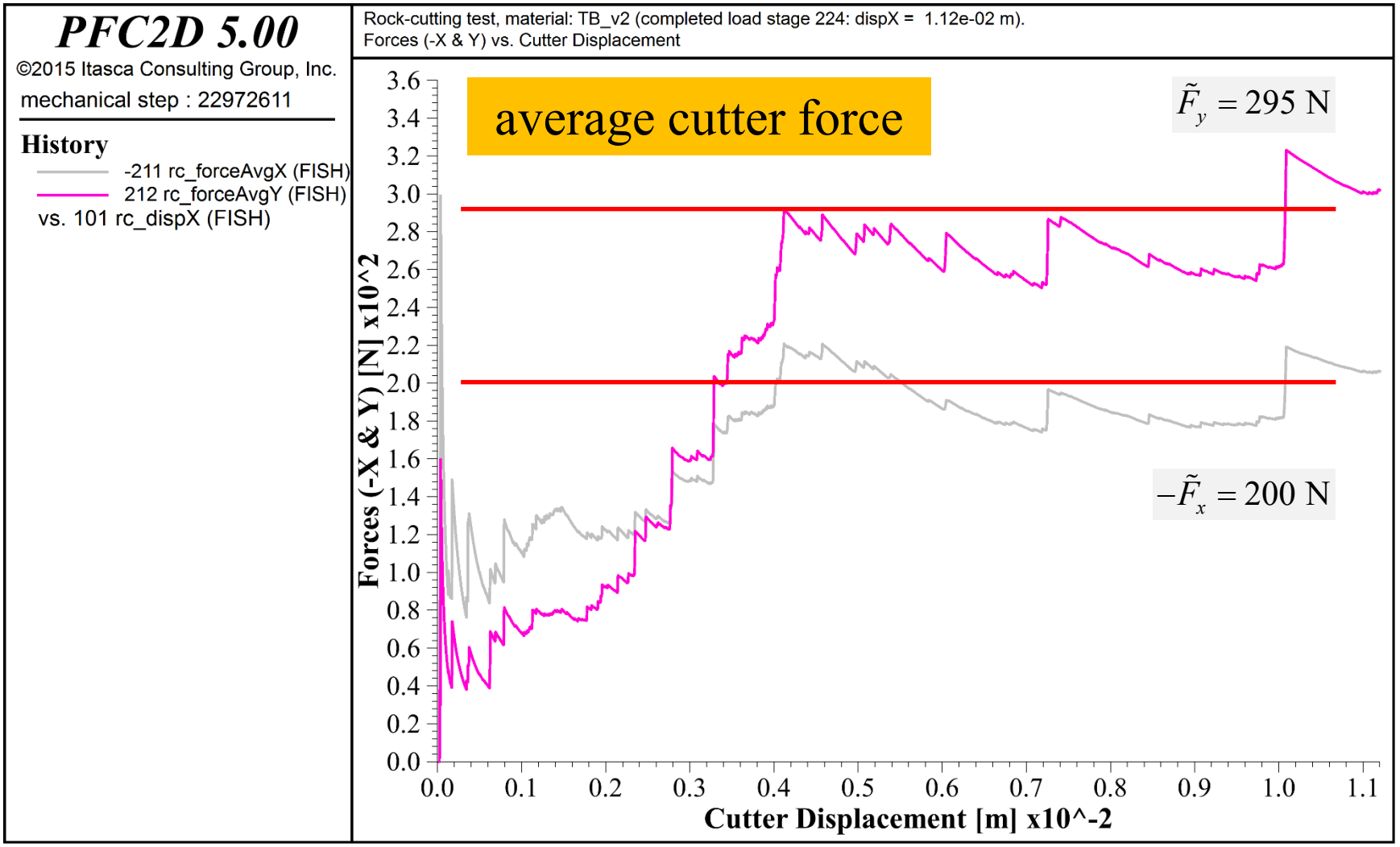


24.0 mm (480 grains)

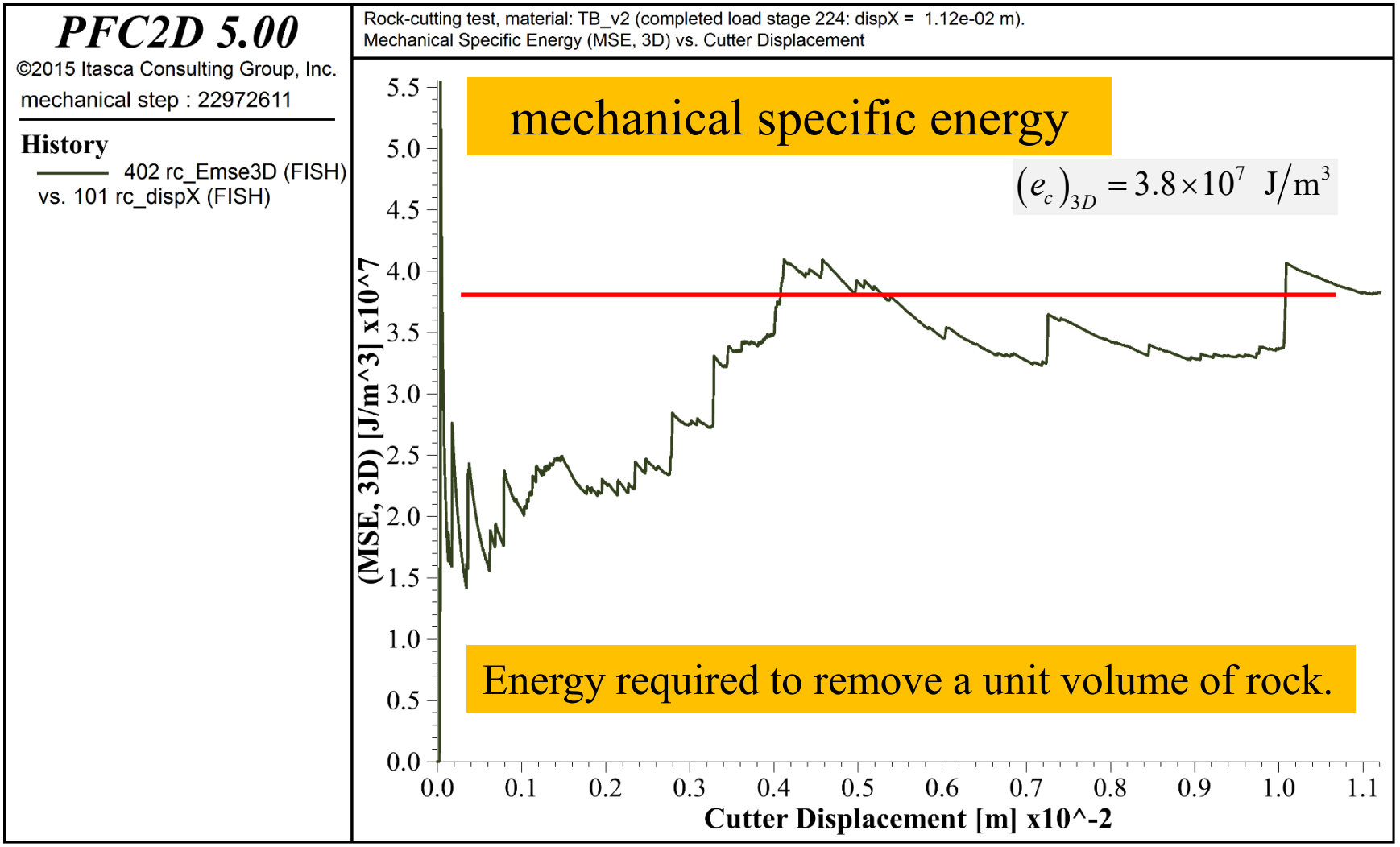
Rock Cutting (quantitative evaluation of 2D dry cutting)



Rock Cutting (quantitative evaluation of 2D dry cutting)

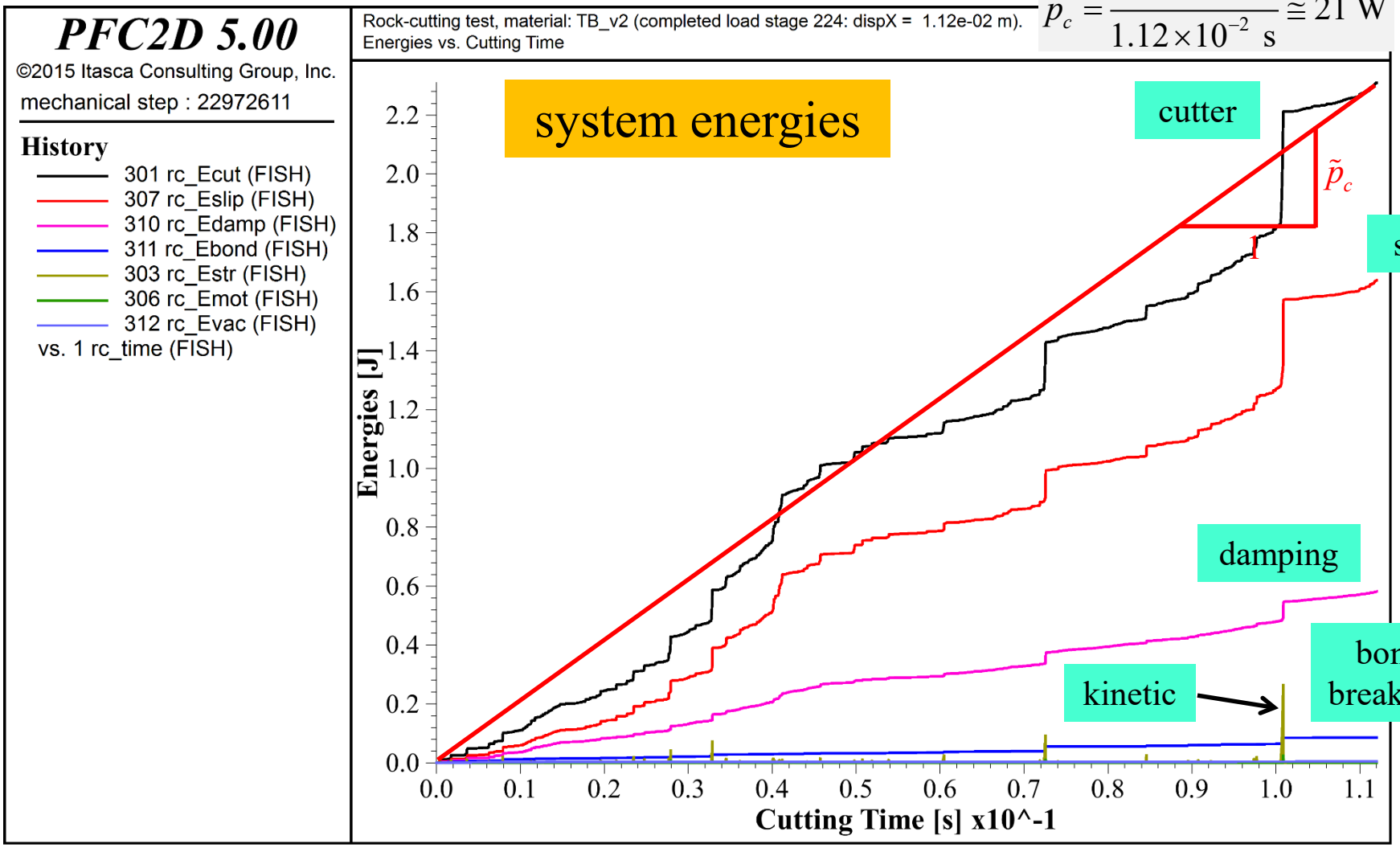


Rock Cutting (quantitative evaluation of 2D dry cutting)

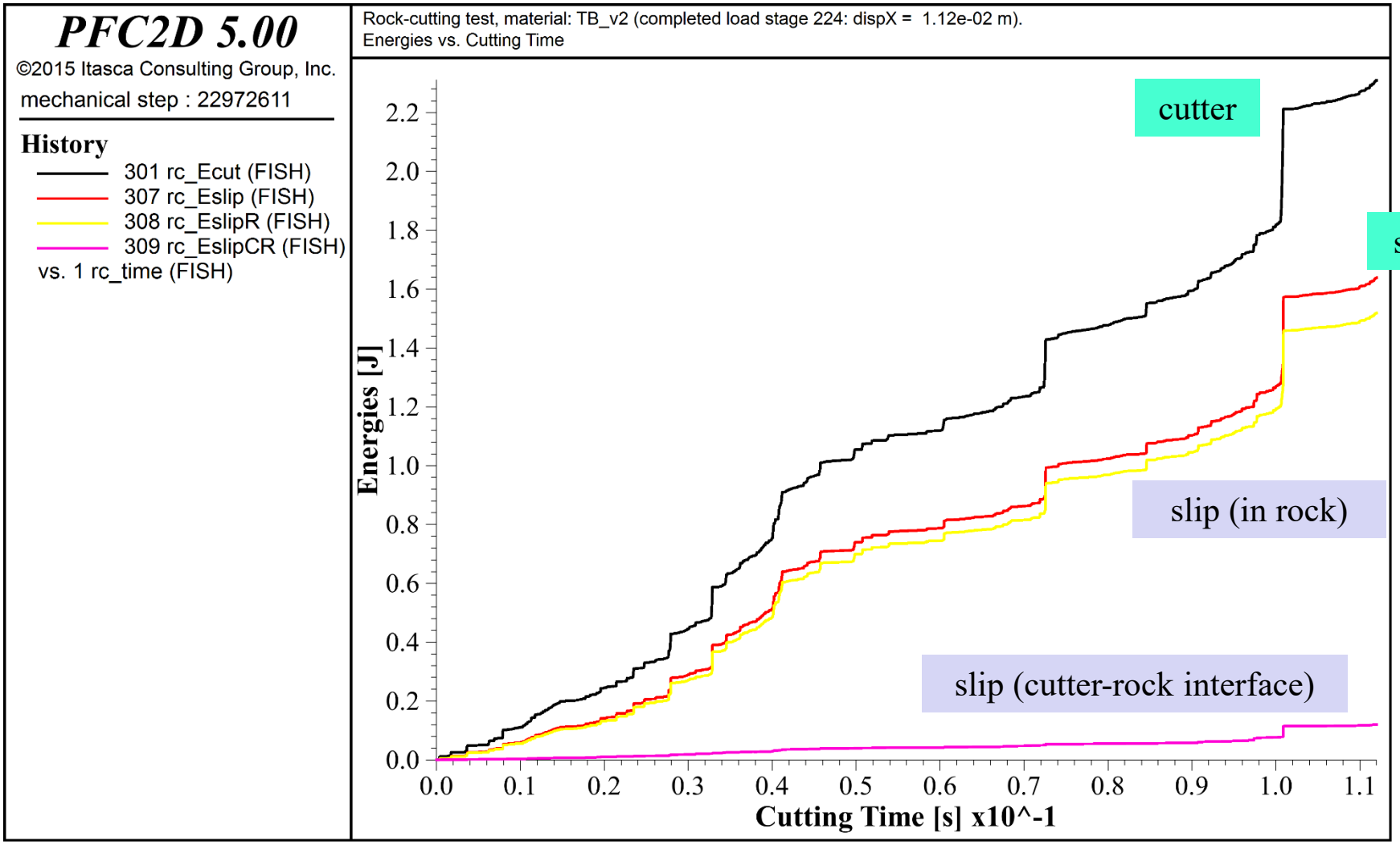


Rock Cutting (quantitative evaluation of 2D dry cutting)

$$\tilde{p}_c = \frac{2.31\ \text{J}}{1.12\times10^{-2}\ \text{s}} \cong 21\ \text{W}$$

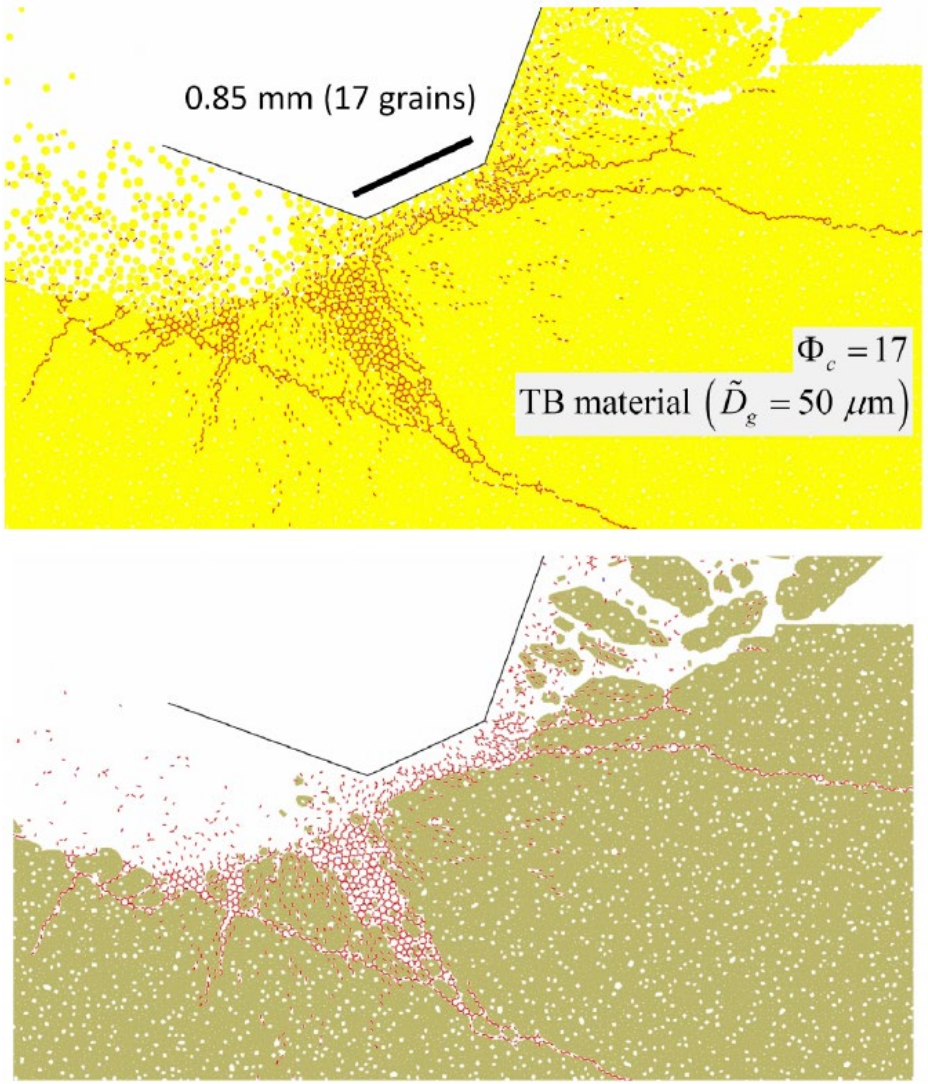


Rock Cutting (quantitative evaluation of 2D dry cutting)



Rock Cutting (quantitative evaluation of 2D dry cutting)

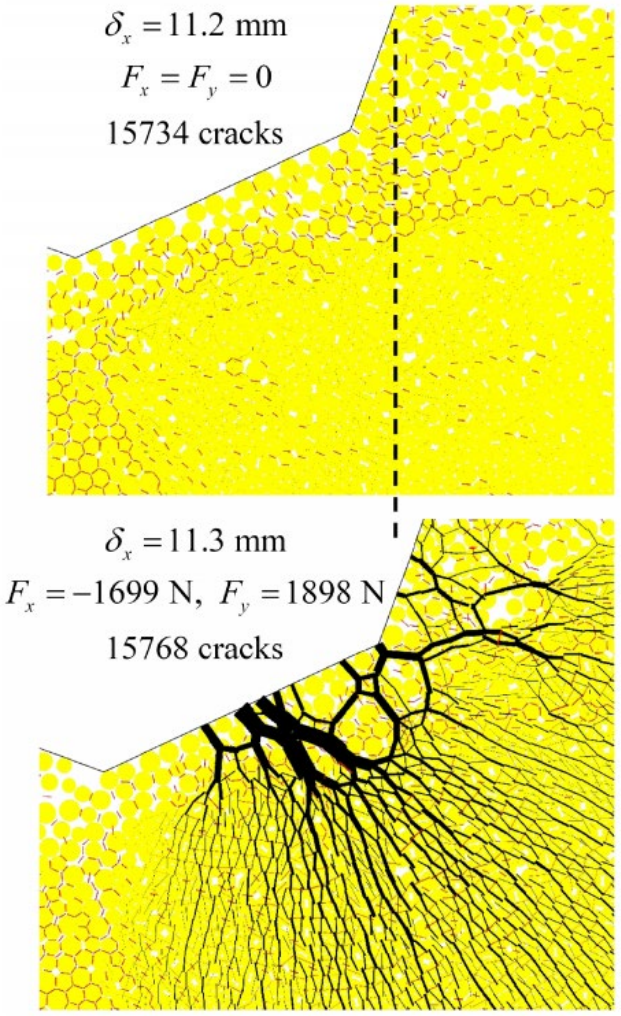
The broken material in contact with the cutter consists of fully unbonded grains.



Near-cutter damage in TB material ($\tilde{D}_g = 50\ \mu$m) after 11.2 mm of cutter displacement.

Rock Cutting (quantitative evaluation of 2D dry cutting)

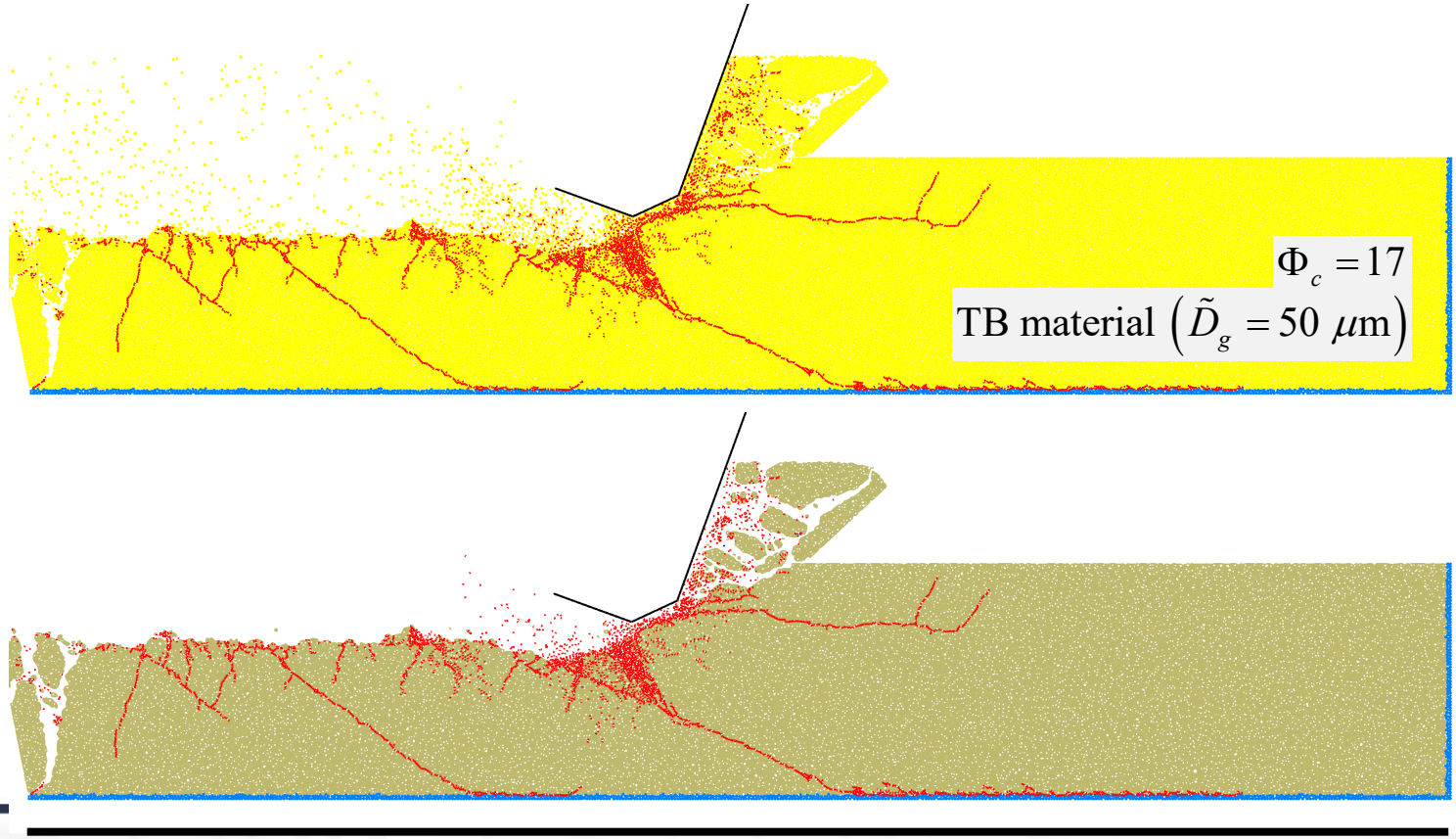
The behavior of the cutter-rock system consists of repeated episodes of cutter force build-up followed by localized damage near the cutter and stress redistribution during which the cutter force drops to zero.



Cutter force build-up in TB material ($\tilde{D}_g = 50$ μm) after 11.2 and 11.3 mm of cutter displacement showing force chains (scaled to same magnitude), filtered cracks with gap less than 50 microns (50% size), and grains.

Rock Cutting (quantitative evaluation of 2D dry cutting)

Similar rock-cutting properties are obtained for the TB material with a grain size equal to that of Torrey Buff sandstone, and for grain sizes that are two and four times larger.



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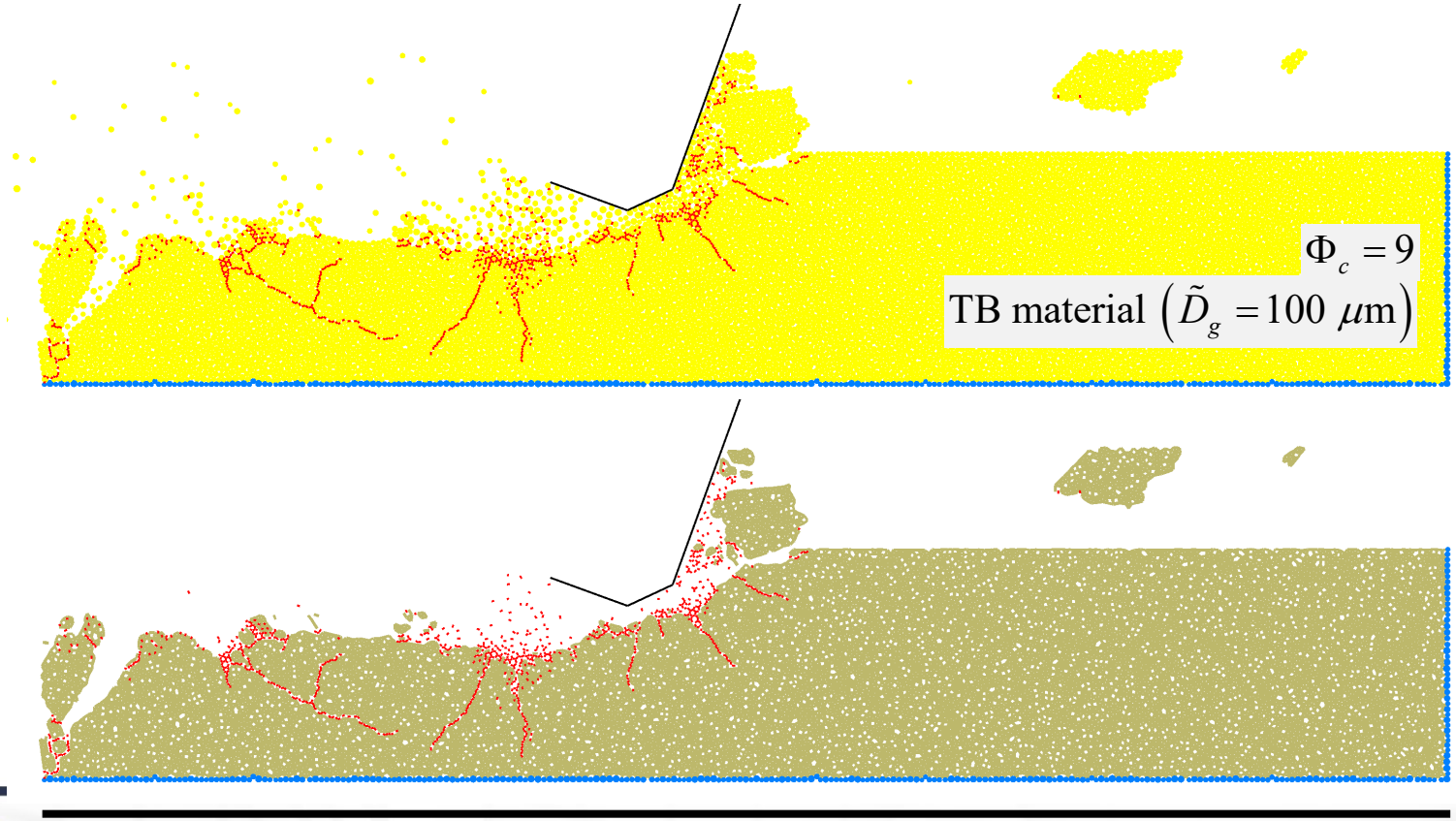

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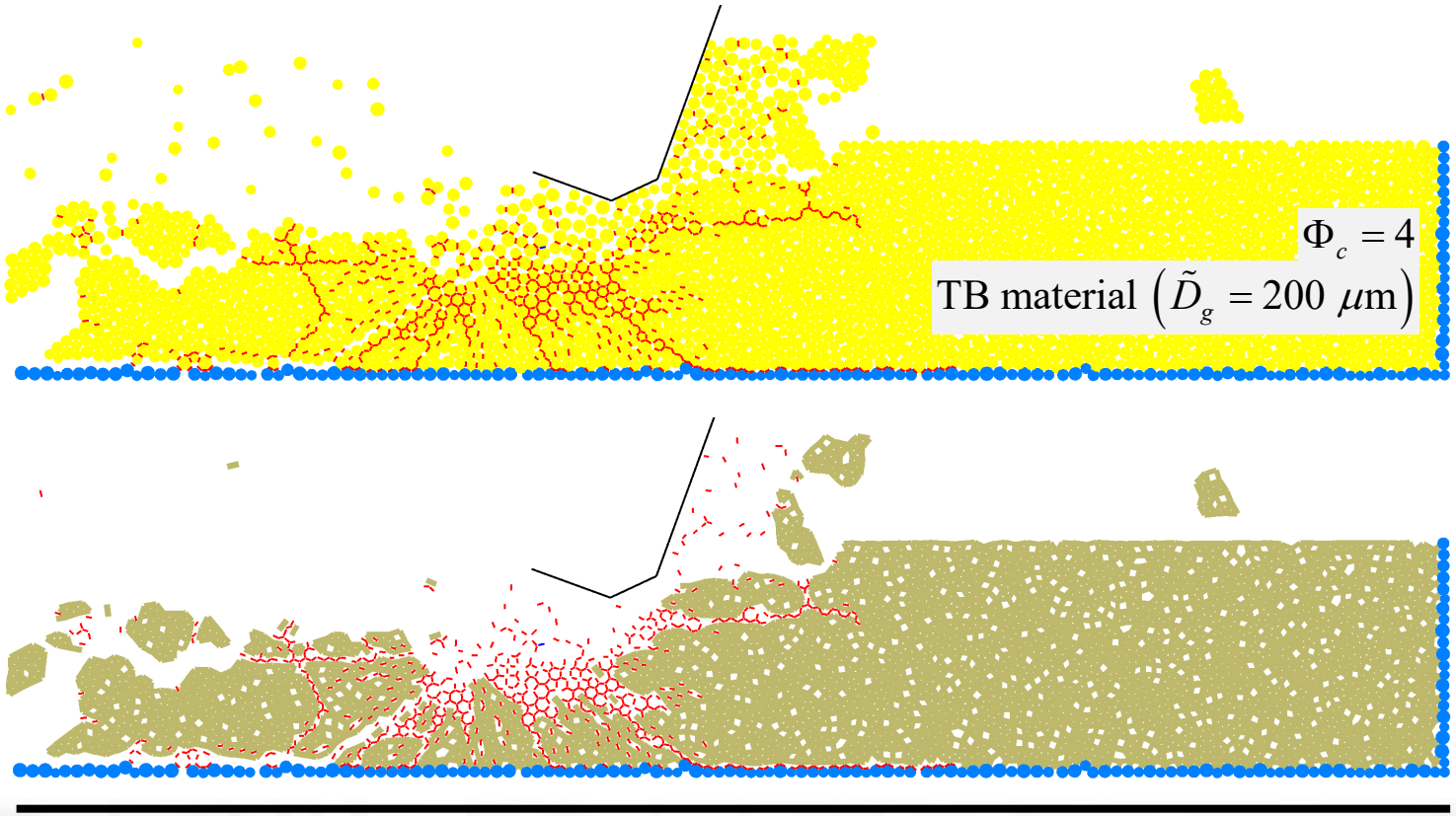


Rock Cutting (quantitative evaluation of 2D dry cutting)

The largest grain-size material has four grains across the chamfer width, and this appears to be sufficient to resolve the effect of this chamfer on the cutter force.

The largest grain-size material could be used to perform a parametric study of cutter-rock behavior.

runtimes

TB material $\left(\tilde{D}_g = 50\ \mu\text{m}\right)$: 11 days, 11-mm cutter displacement

TB material $\left(\tilde{D}_g = 100\ \mu\text{m}\right)$: 64 hours, 22-mm cutter displacement

TB material $\left(\tilde{D}_g = 200\ \mu\text{m}\right)$: 7 hours, 22-mm cutter displacement

Rock Cutting (2D wet cutting)

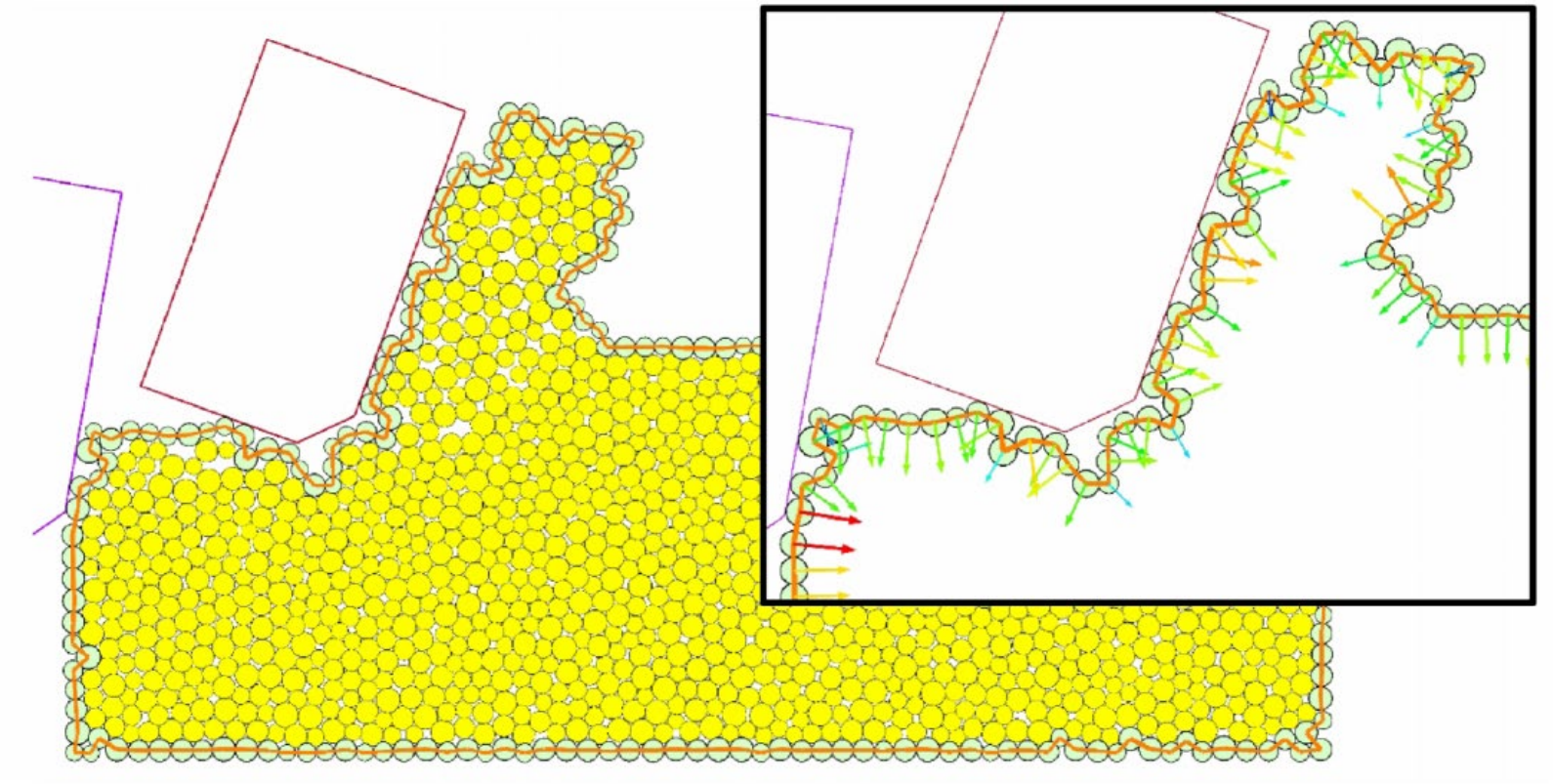
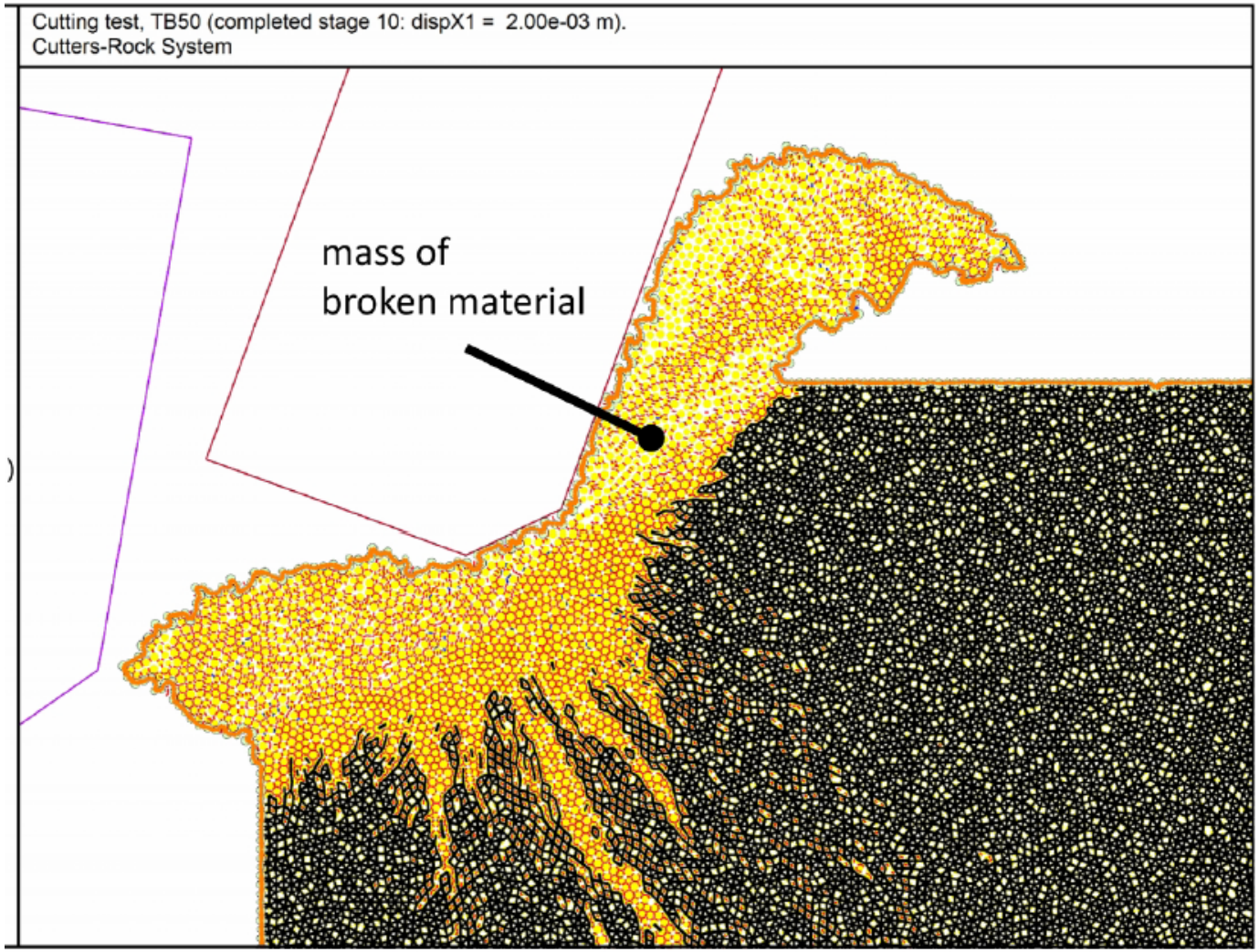


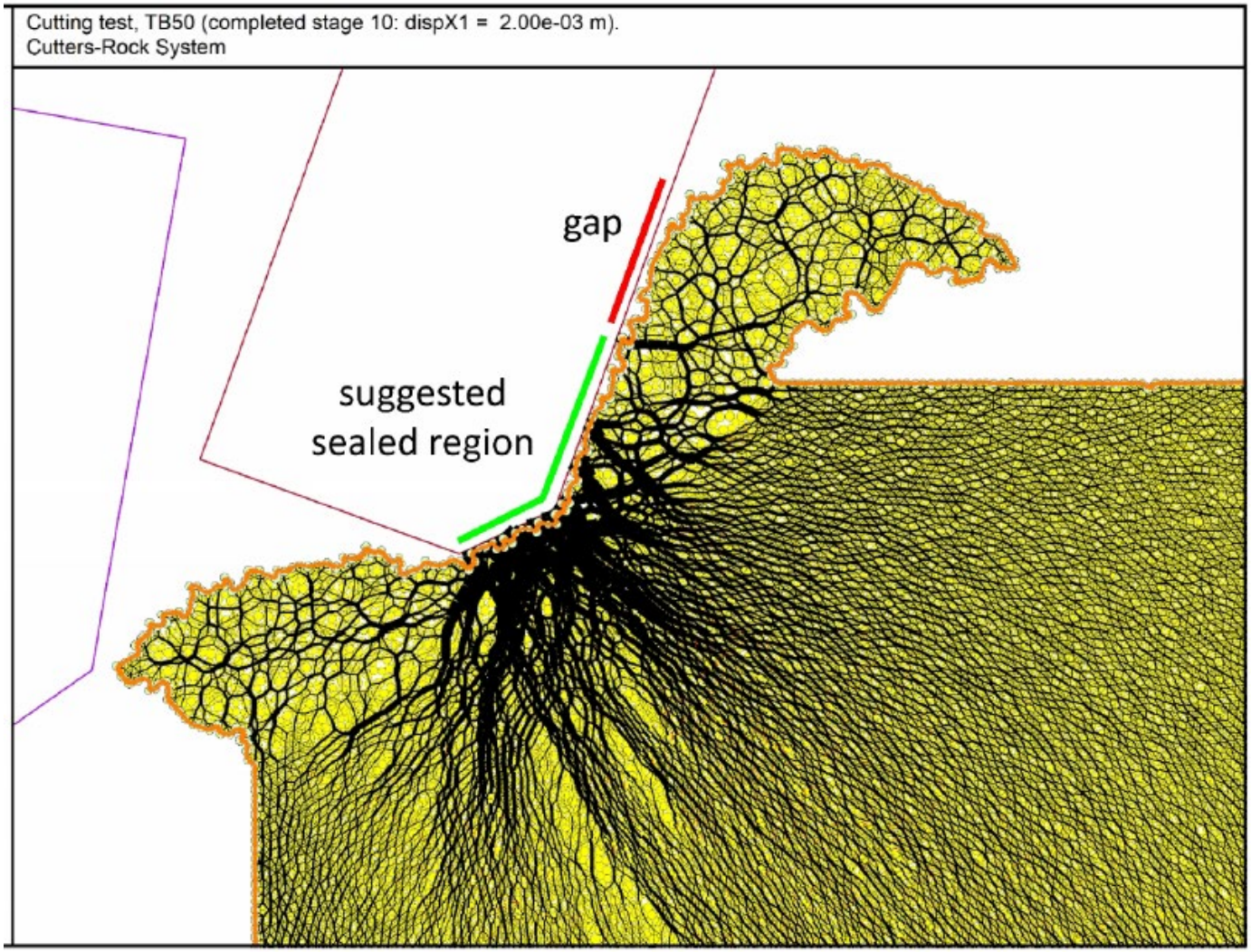
Figure 4 *Pressure-application chain (no chain seals) with 5-MPa confining pressure acting on the base case cutting-test model showing chain balls, chain links, and applied external forces.*

Rock Cutting (2D wet cutting)



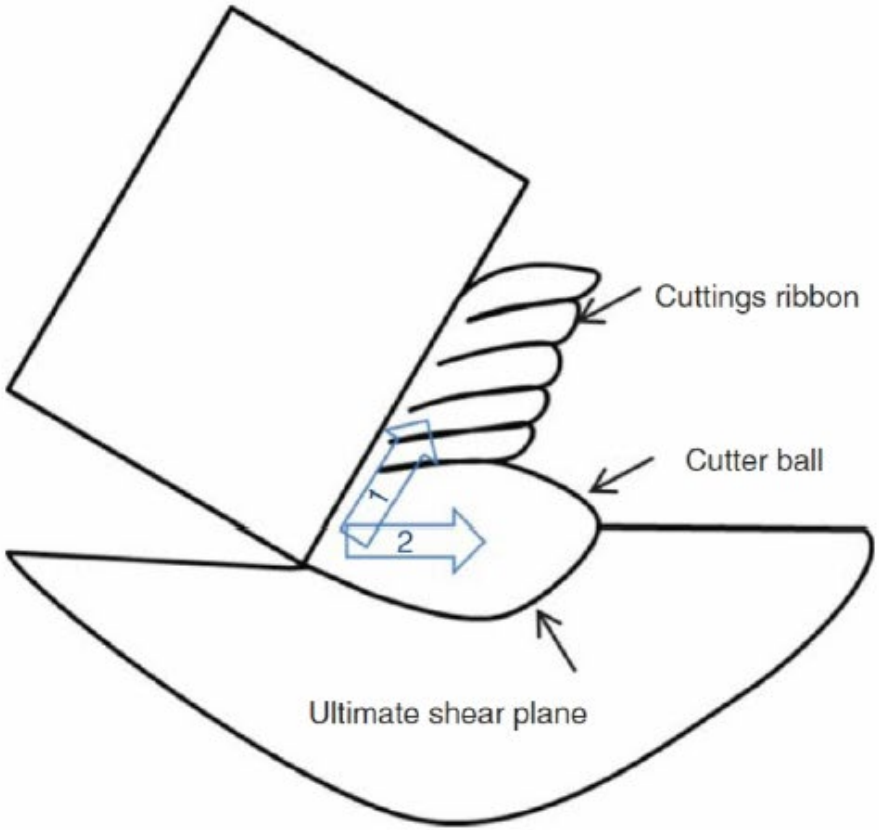
Damage: wet cutting (5 MPa confinement)

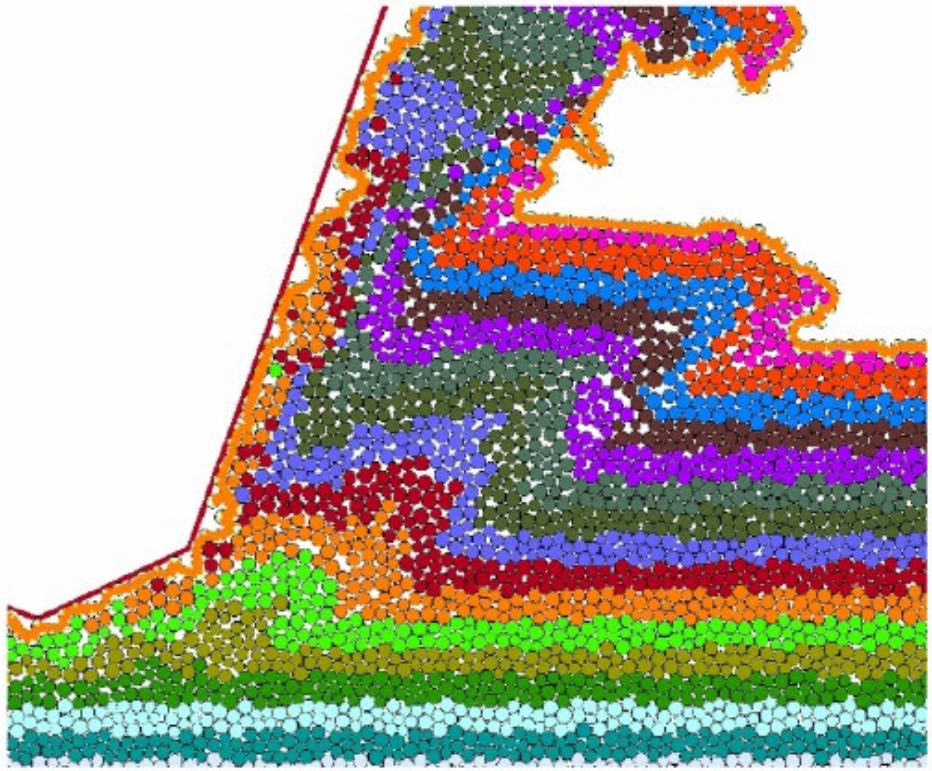
Rock Cutting (2D wet cutting)



Force-chain fabric: wet cutting (5 MPa confinement)

Rock Cutting (2D wet cutting)

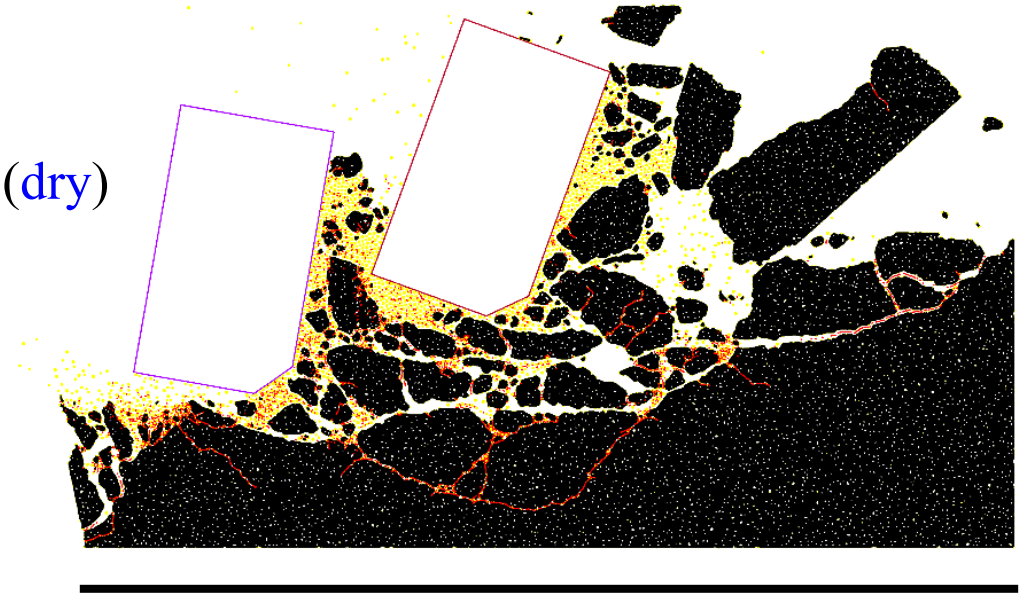




Postulated wet-cutting mechanism:
shear off, then ride up face

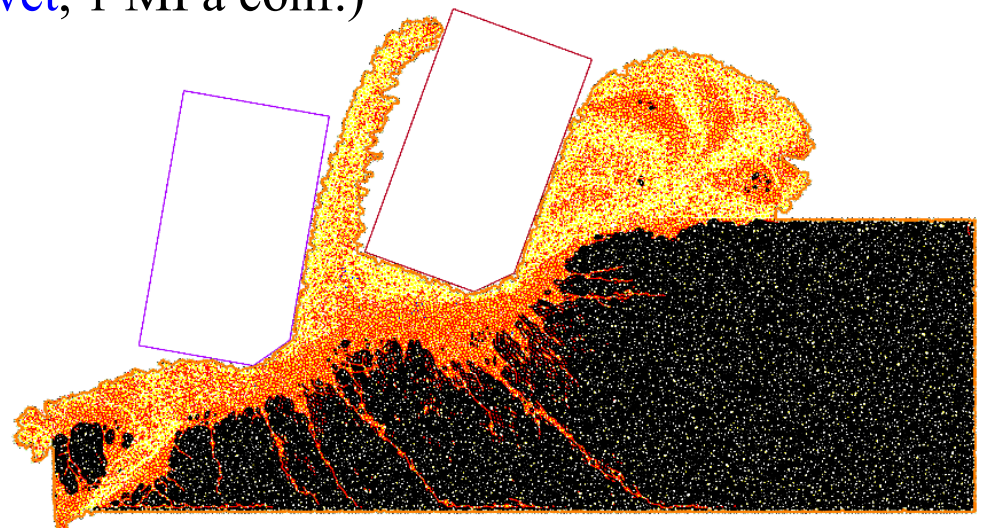
Rock Cutting (comparison of 2D dry & wet cutting)

cutting test (dry)

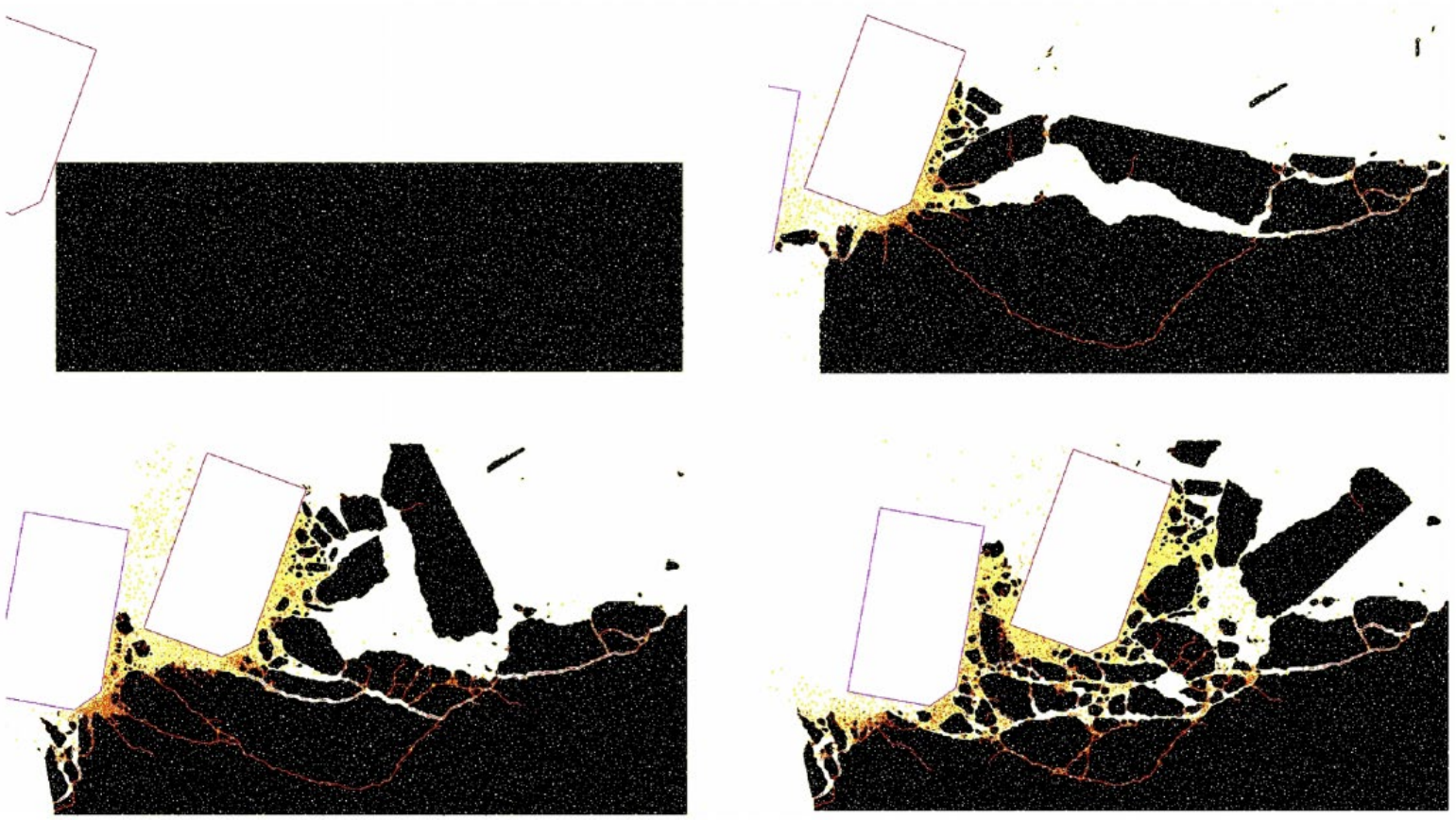


12.0 mm (240 grains)

cutting test (wet, 1 MPa conf.)

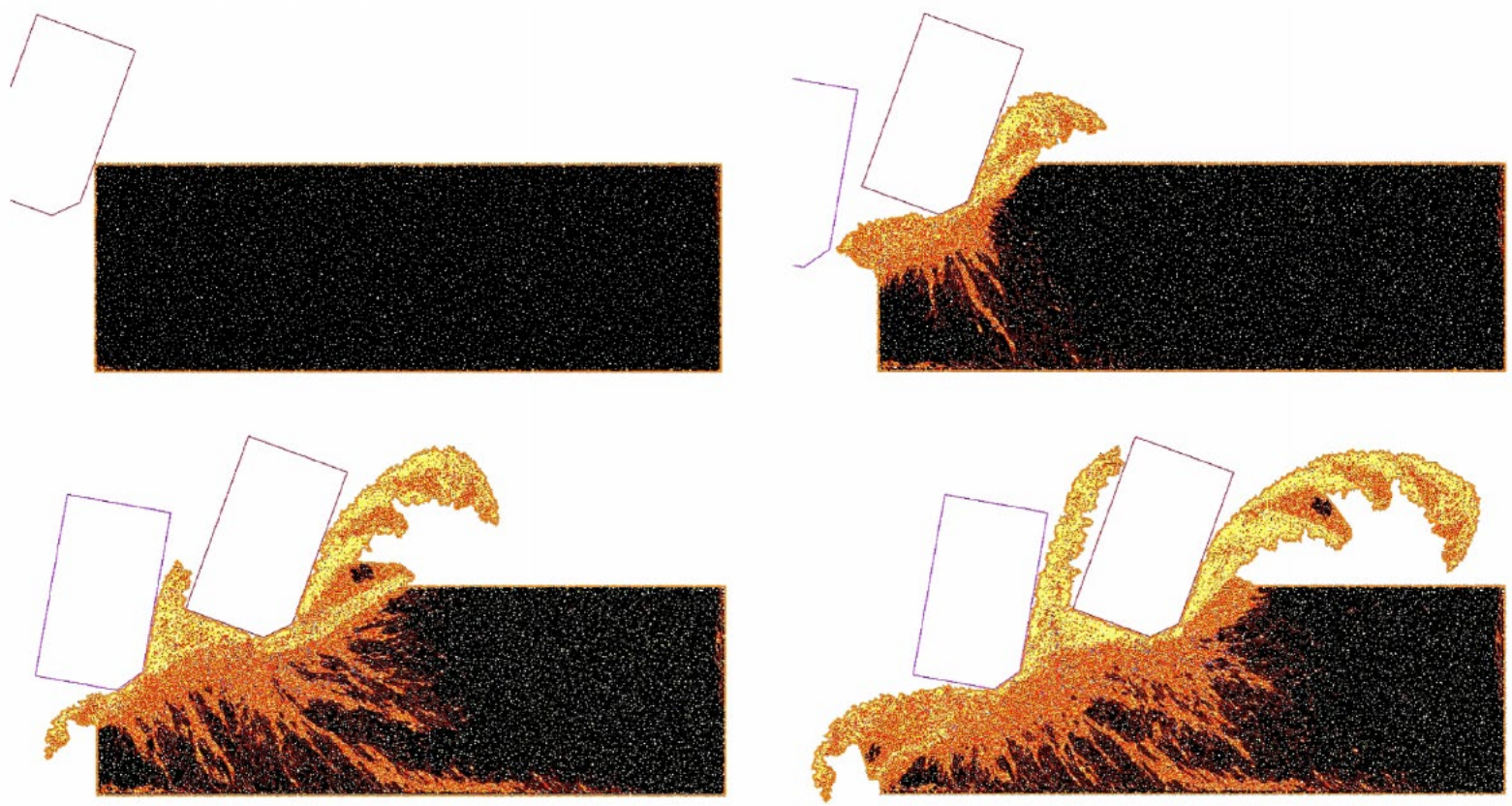


Rock Cutting (comparison of 2D dry & wet cutting)



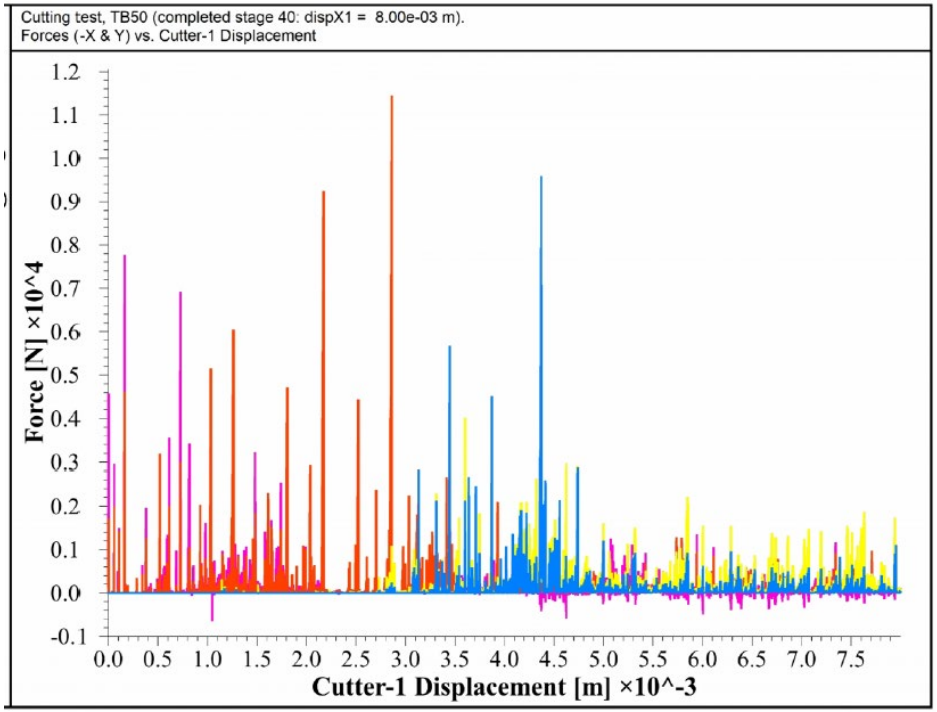
Damage evolution: dry cutting

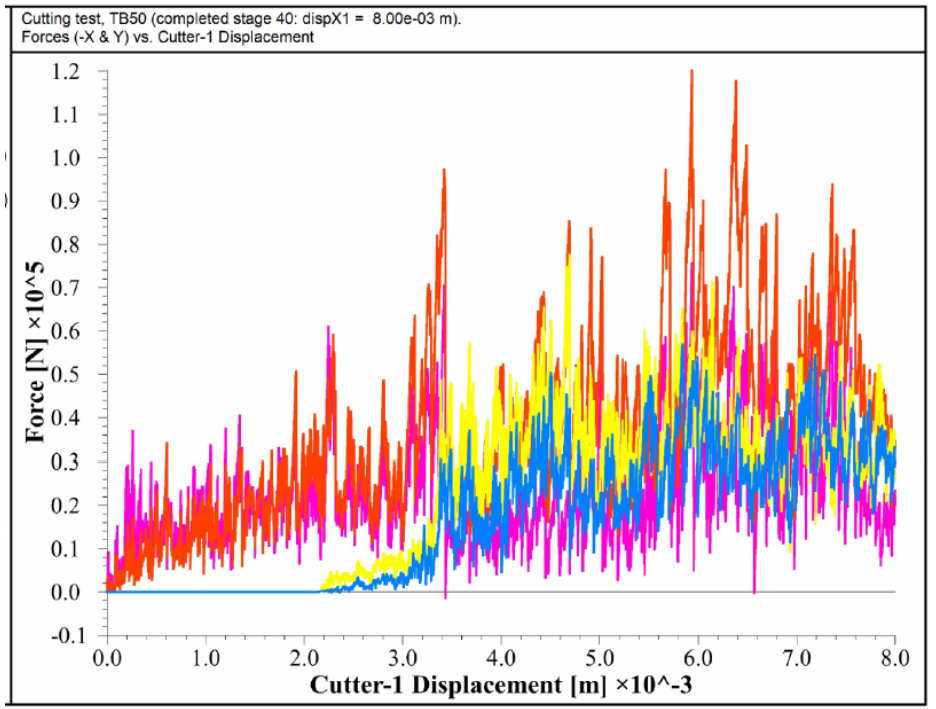
Rock Cutting (comparison of 2D dry & wet cutting)



Damage evolution: wet cutting (5 MPa confinement)

Rock Cutting (comparison of 2D dry & wet cutting)



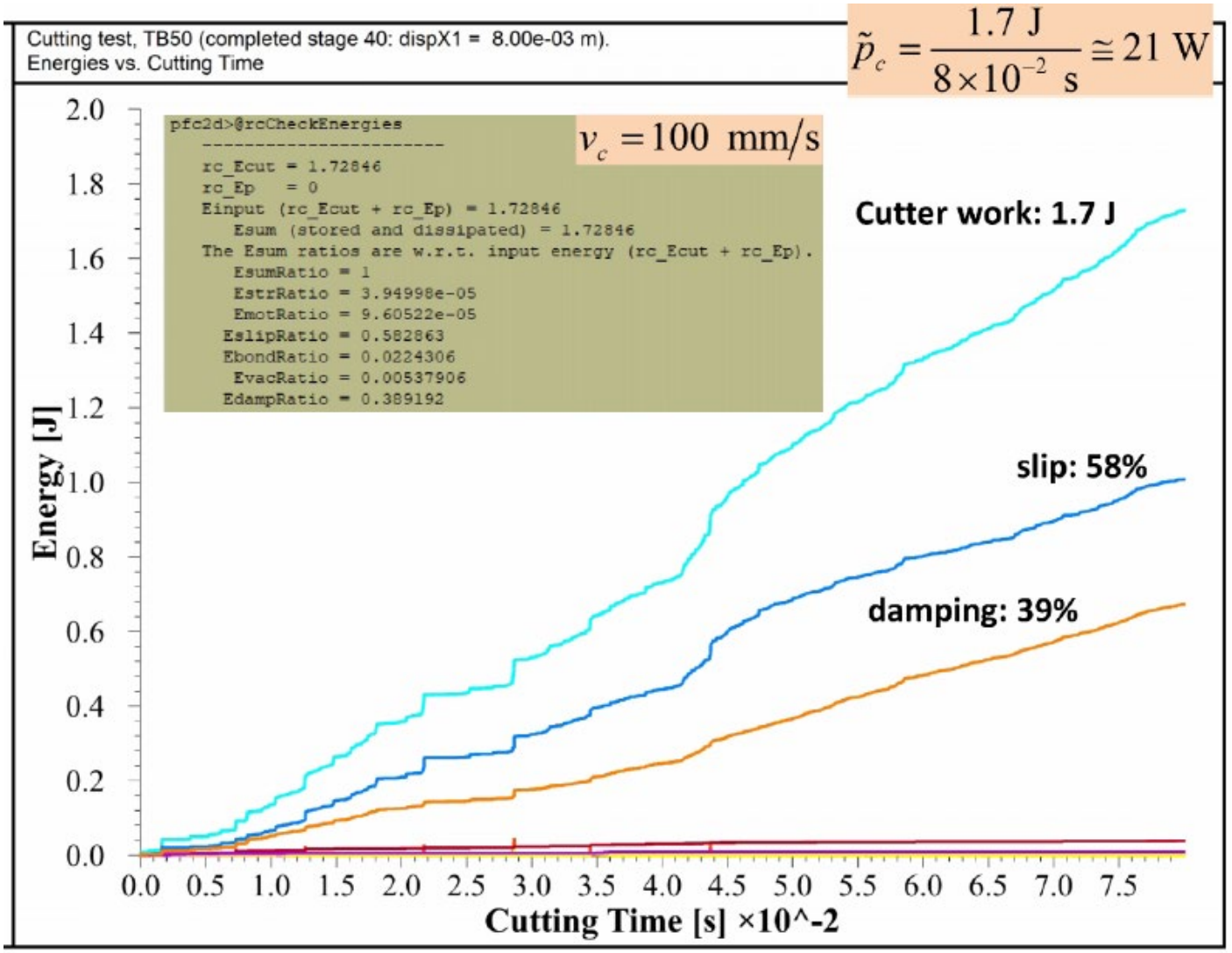


Dry Cutting

Wet Cutting

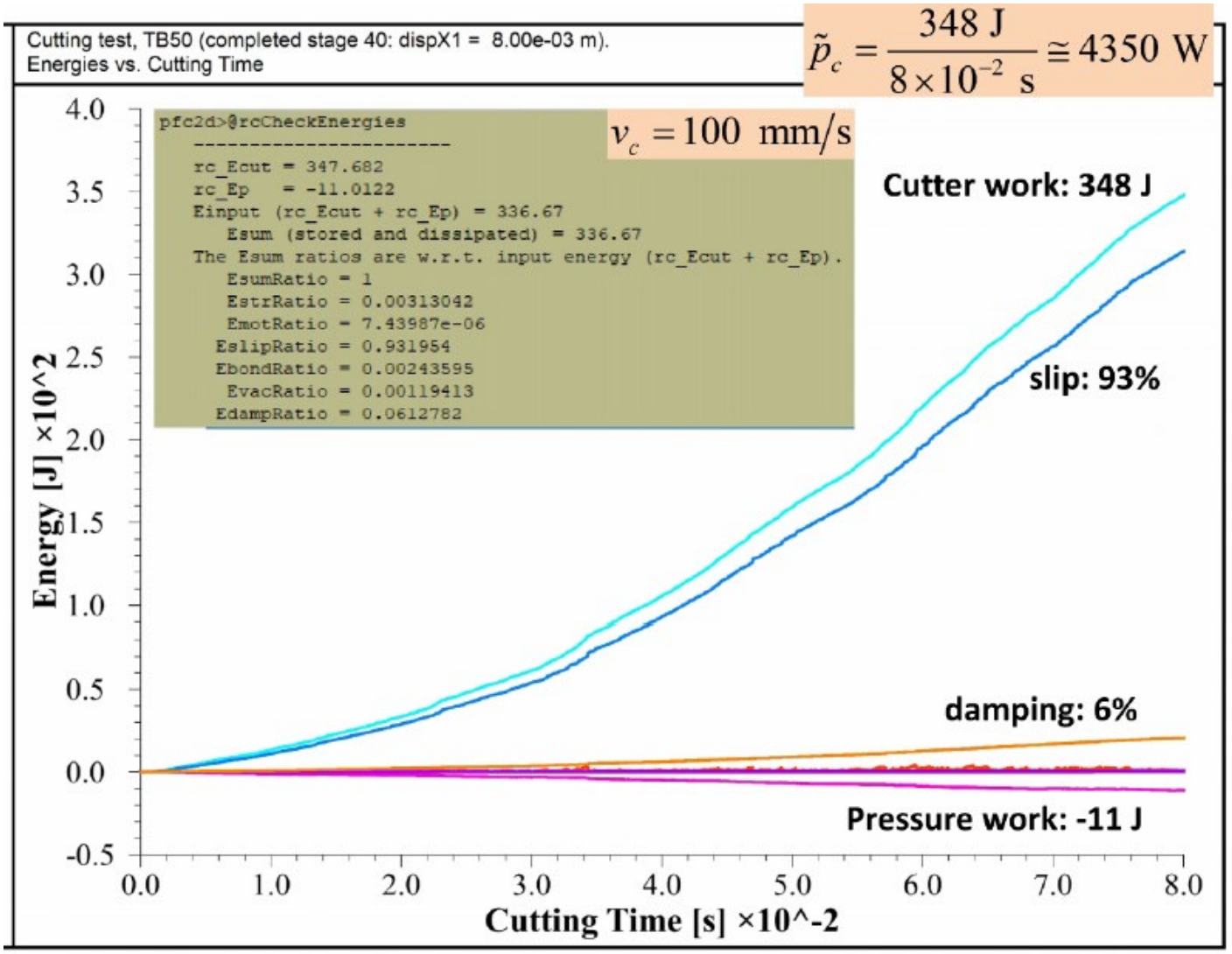
Forces 10 times larger
More continuous (intimate contact)
Fluctuations suggest brittle failure

Rock Cutting (comparison of 2D dry & wet cutting)



Energy partitions: dry cutting

Rock Cutting (comparison of 2D dry & wet cutting)



Energy partitions: wet cutting (5 MPa confinement)

Rock Cutting (conclusions)

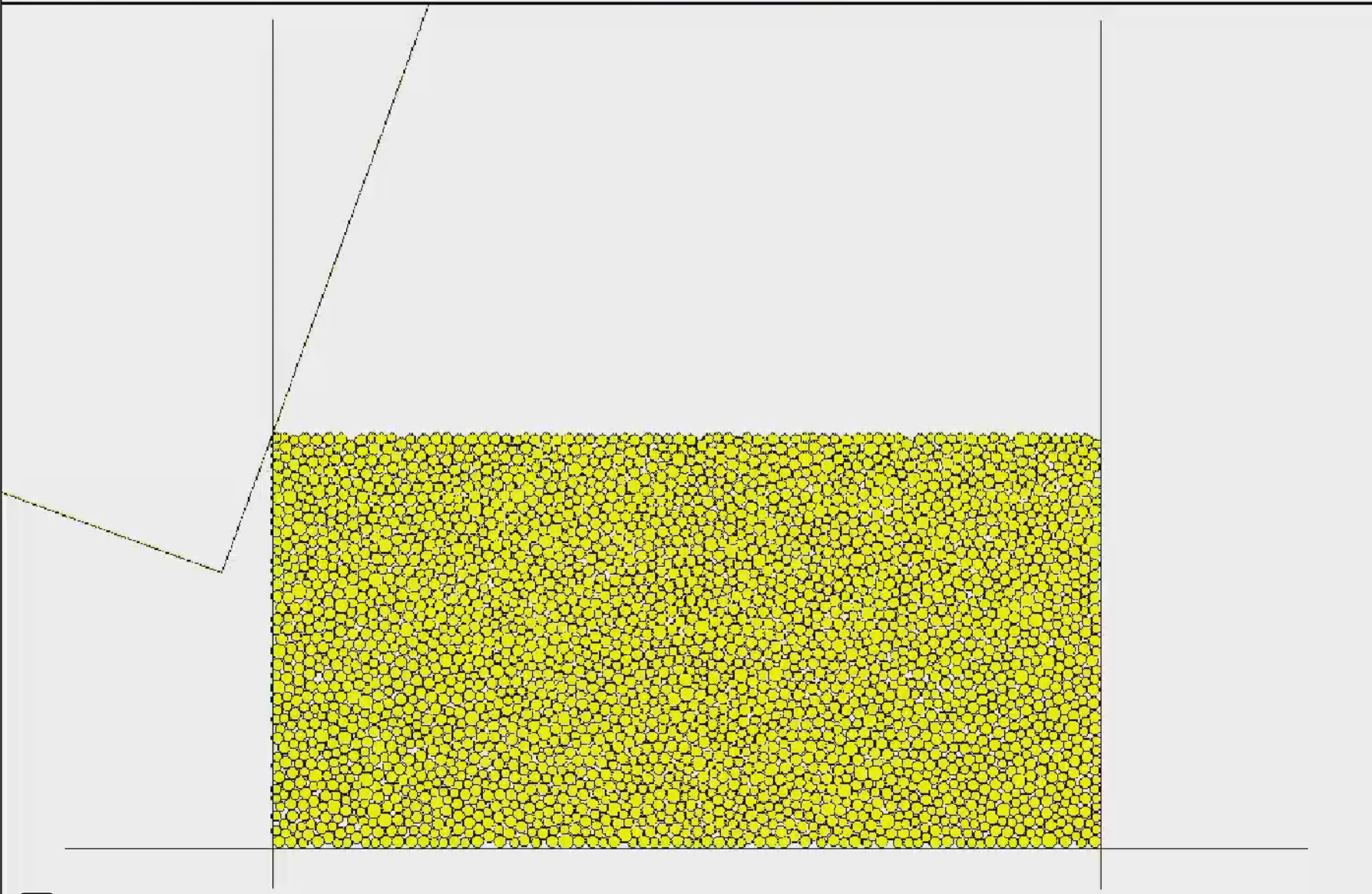
- Relevant mechanisms are exhibited by the model.
  - Effect of dry & wet cutting (pressure inhibits chip formation, requires more energy to cut)

- Perform parametric studies of system behavior.
  - Different rock types can be created by varying the microstructural properties of the synthetic material. The model provides a link between rock microstructure and cutter geometry.

- The model produces qualitative agreement between synthetic and measured cutting forces; and thus, the model may be used to comparatively evaluate alternative rock types and cutter designs.

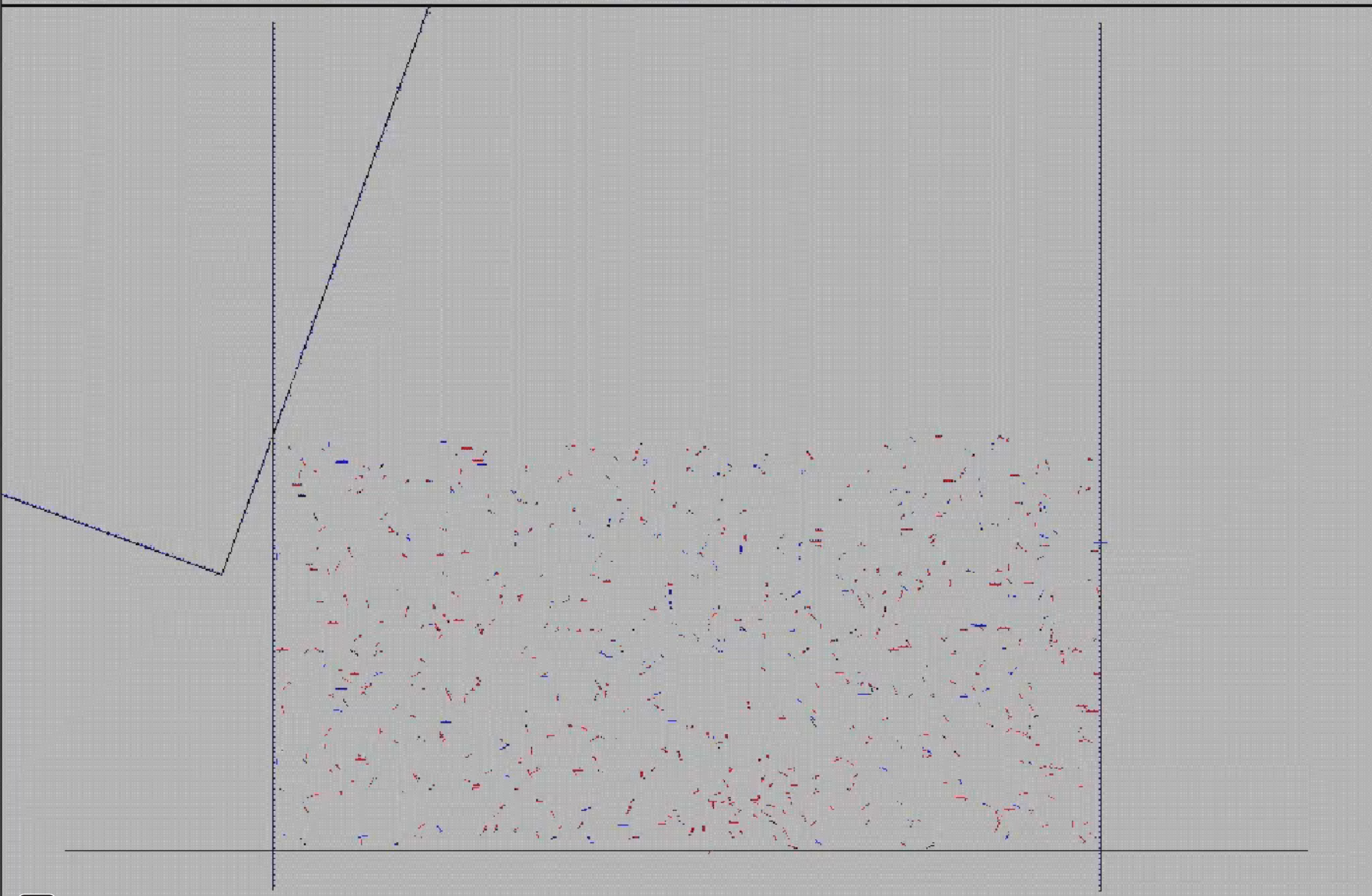
Job Title: sB1_mB_bM-ct0

View Title: Damage (P = 0 MPa) at 000e-1 mm penetration (0 cracks, tensile/shear=red/blue=0/0)



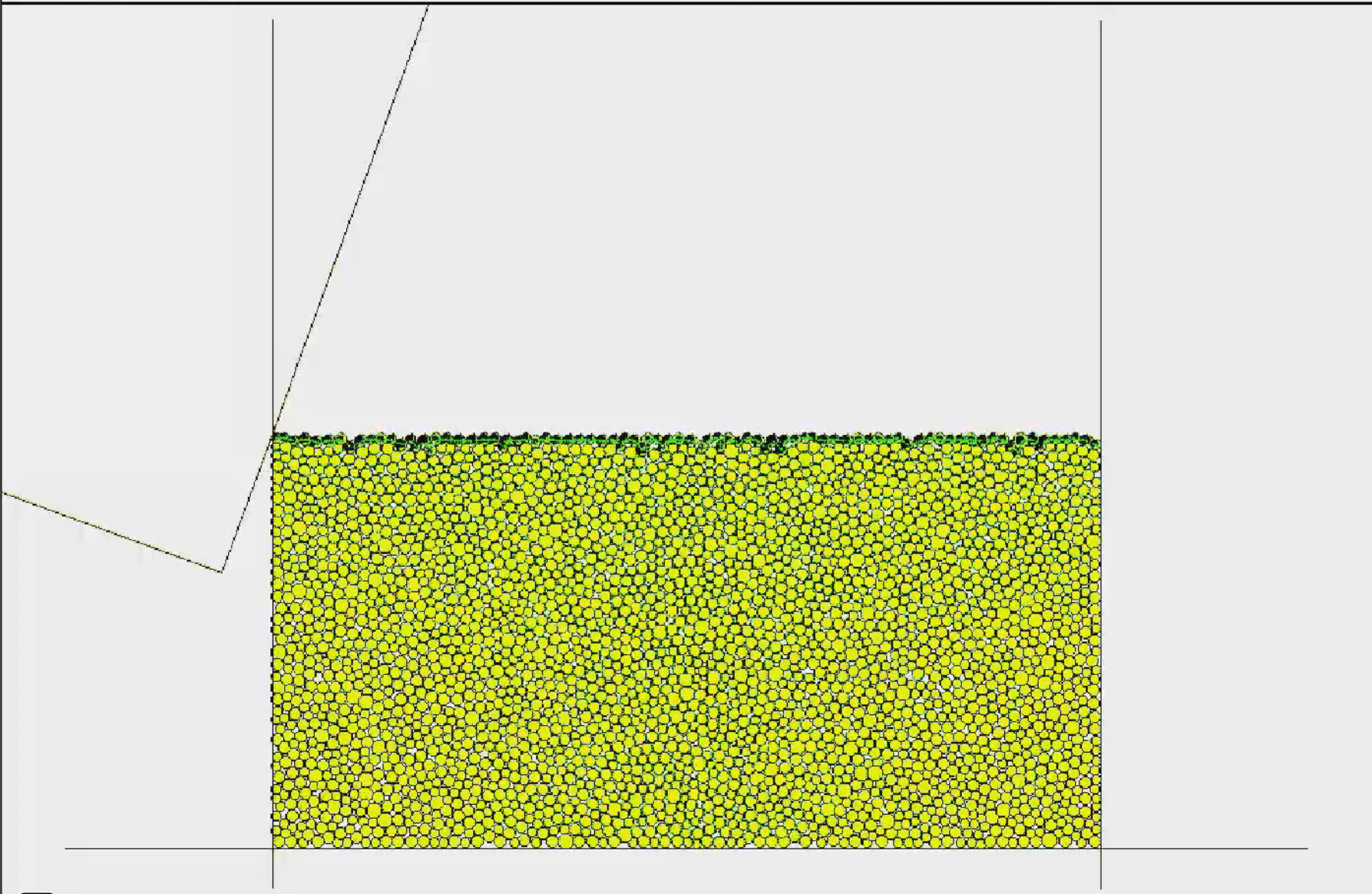
Job Title: sB1_mB_bM-ct0

View Title: Forces (P = 0 MPa) at 000e-1 mm penetration (blue & black/red=compression/tension, maxpf/maxcf=7/42 kN)



Job Title: sB1_mB_bJ-ct0

View Title: Damage (P = 5 MPa) at 000e-1 mm penetration (0 cracks, tensile/shear=red/blue=0/0)



PFC2D 6.00

Mechanical step : 7881

TB50 material removed from physical vessel.
Cutters-Rock System

Wall name

No objects fit the plot criteria.

- cutter1
- cutter2

Ball

- ball

Contact pb_state

- 3

Fracture group 2

No objects fit the plot criteria.

Fractures (0)

- PB-shearFail(gap < 5e-05)
- PB-tenFail(gap < 5e-05)

Ball group chain

Balls (23162)

Contact group chain

Contacts (65572)

PFC2D 6.00

Mechanical step : 7881

TB50 material removed from physical vessel.
Cutters-Rock System

Wall name

No objects fit the plot criteria.

- cutter1
- cutter2

Contact force_mag

No objects fit the plot criteria.

Contacts (0)

- 1.0000E+3
- 9.0000E+2
- 8.0000E+2
- 7.0000E+2
- 6.0000E+2
- 5.0000E+2
- 4.0000E+2
- 3.0000E+2
- 2.0000E+2
- 1.0000E+2
- 0.0000E+0

PFC2D 6.00

Mechanical step : 7881

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- cutter1
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Ball

- ball

Contact pb_state

- 3

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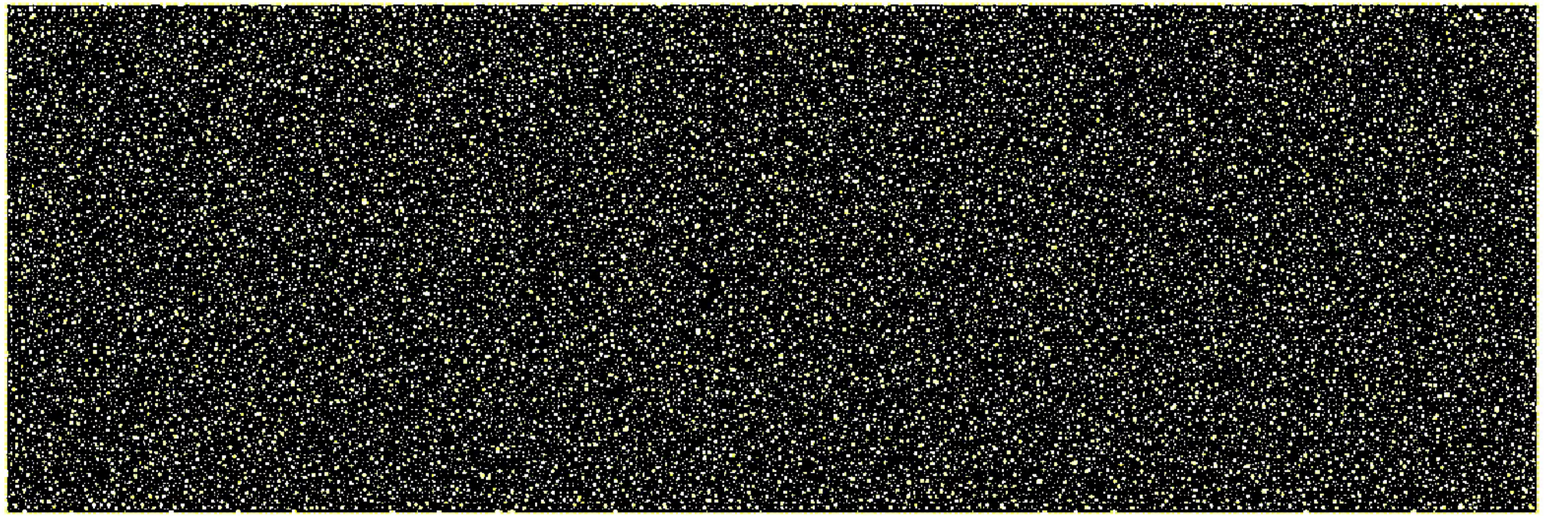
TB50 material removed from physical vessel.
Cutters-Rock System



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Cutters-Rock System

Contact force_mag

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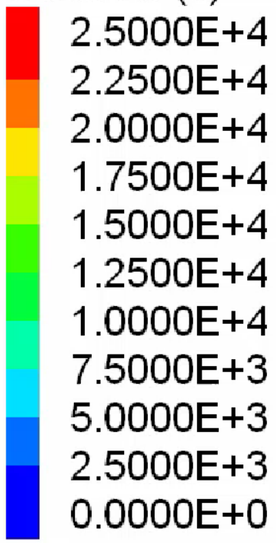
Contacts (0)



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Contact group chain

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