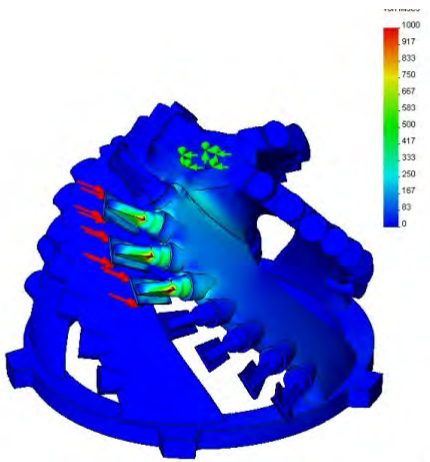
Discrete element modeling of circular rock cutting

with evaluation of pore pressure effects



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June 16th 2016 **WODCON XXI: Innovations in Dredging**

Agentschap NL
Ministerie van Economische Zaken, Landbouw en Innovatie

Boskalis
Van Oord
IHC

Section Dredging Engineering

TU Delft
Delft University of Technology

Contents

Objectives

Research for applications:

- Dredging at larger depths
- Deep sea mining
- Drilling (oil/gas industry)

Common interest:

Cutting of saturated rock in a high pressure environment

Objectives

To describe the physics of the cutting **process**, in which the focus is on:

- Influence of fluid pressure
- Validation and verification of numerical model

Eventually, this must lead to:

- Improvement of existing models
- Advices for design and workability

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Physical phenomena

Cutting of rock is characterized by

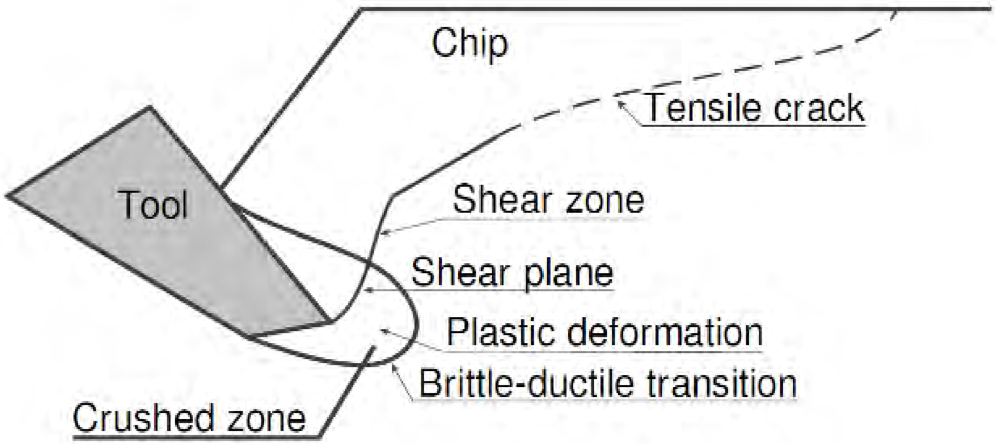
Small cutting thickness (<mm)
- Indentation (crushed zone)
- Plastic flow

Large cutting thickness (mm-cm)
- Indentation (crushed zone)
- Shear crack
- Tensile crack

Image from Huang et al.[1]

Physical phenomena

Failure during cutting covers the whole range of the Mohr envelope (macro failure)

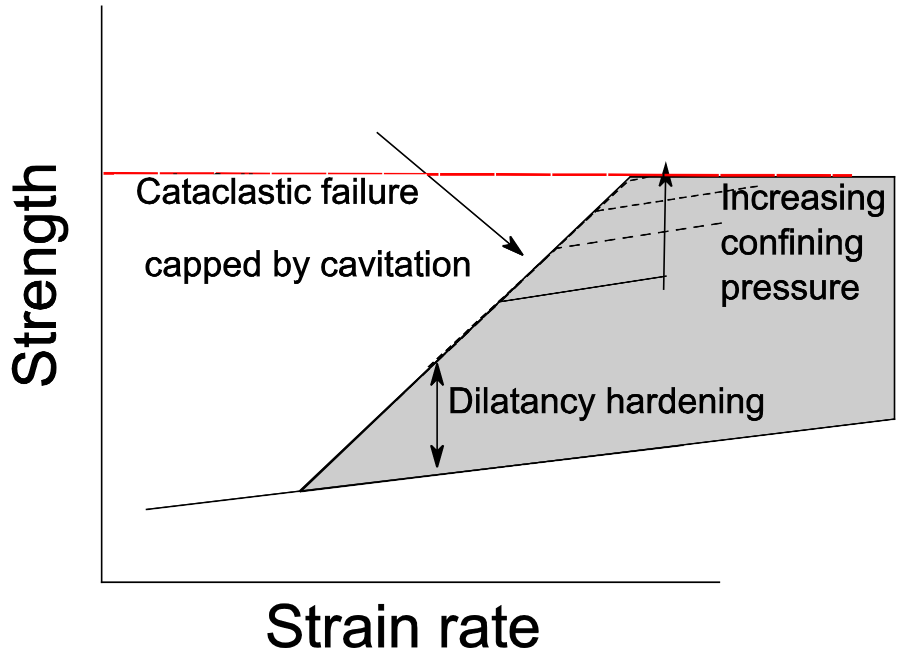


Van Kesteren[2]

Physical Phenomena

Fluid pressure effects:

- Dilatant hardening
- Cataclastic failure
- Hydrostatic pressure/ cavitation



Physical phenomena

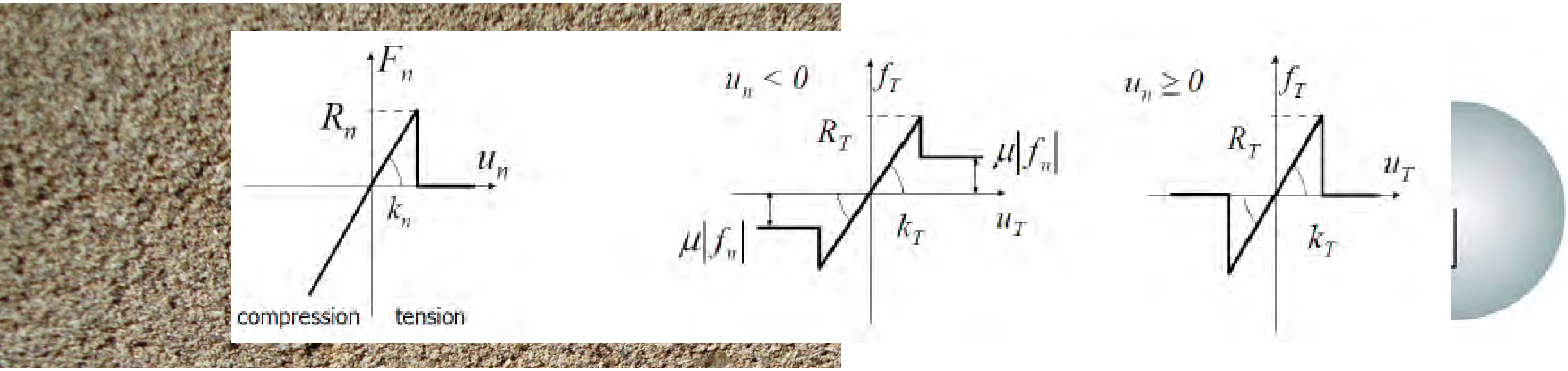
Failure during cutting covers the whole range of the Mohr envelope (macro failure)

Hypothesis: Water depth affects the cutting process

Discrete Element Method

Many particle simulation technique

- Equations of motion: $m_i \frac{d^2\vec{r}}{dt^2} = \vec{f_i}$
- Contact bond model – elastic perfect brittle
- Contact collision model - Mohr friction model
- Currently in 2D



Modeling approach - Fluid

Influence fluid pressure

- Mass balance $\frac{\partial \zeta}{\partial t} + q_{i,i} = 0$
- Darcy flow $q_i = -\frac{k}{\mu} \nabla p$
- Compressibility pore-fluid $p = M(\zeta - \alpha \epsilon_v)$

Gives Poro-elasticity theory: $\frac{\partial p}{\partial t} - \frac{k}{\mu} M \nabla^2 p = -\alpha M \frac{\partial \epsilon_v}{\partial t}$

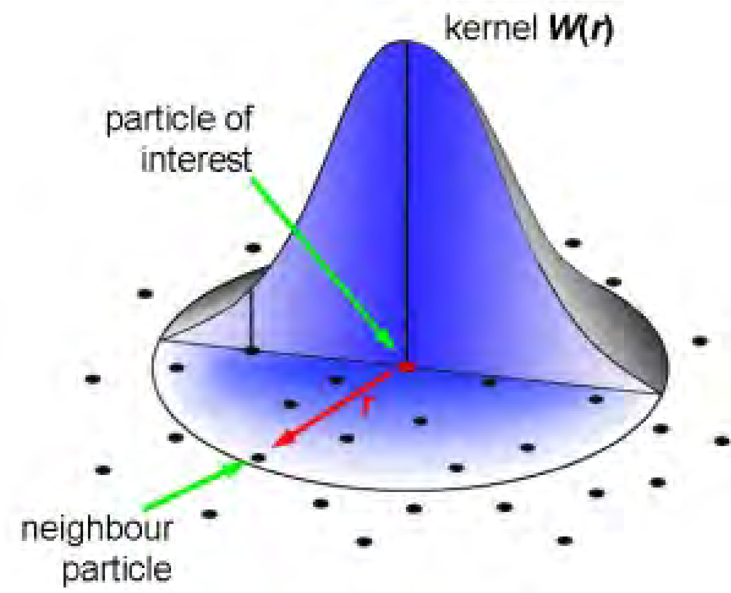
Note: Failure criteria of rock do **not** change, only stress state in/on the rock changes

Smoothed Particle

Meshless method

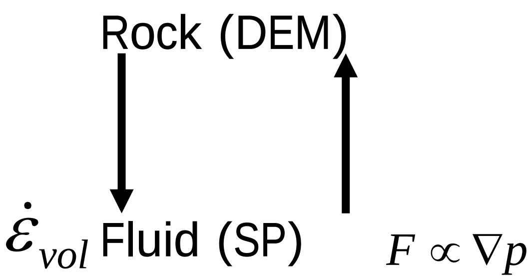
- Interpolation technique using kernel function
- $A(\vec{x}_i) = \sum_j A_j \frac{m_j}{\rho_j} W(\vec{x}_i - \vec{x}_j, h)$
- $\nabla A(\vec{x}_i) = \sum_j A_j \frac{m_j}{\rho_j} \nabla W(\vec{x}_i - \vec{x}_j, h)$

Used to solve fluid pressure



Coupling in DEM-SP

- Change of pore volume: Volumetric strain $\dot{\epsilon}_v = \nabla \cdot \vec{v}$
- Pressure gradient force $\vec{F} = -V_p \nabla p$



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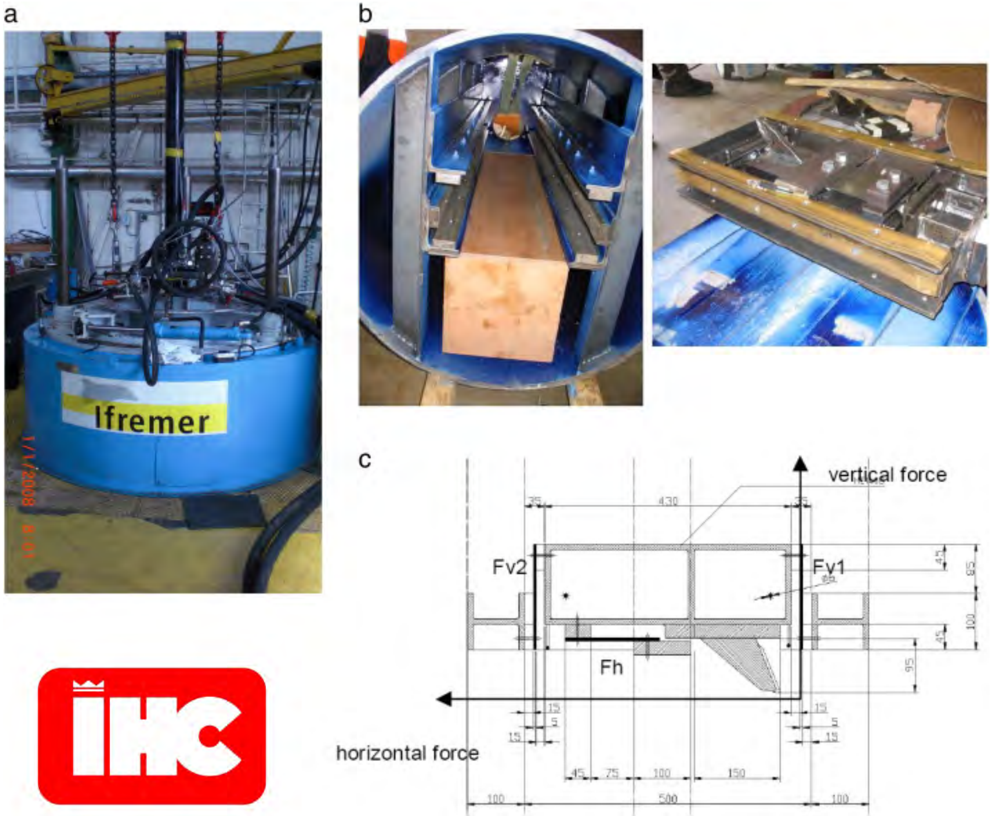
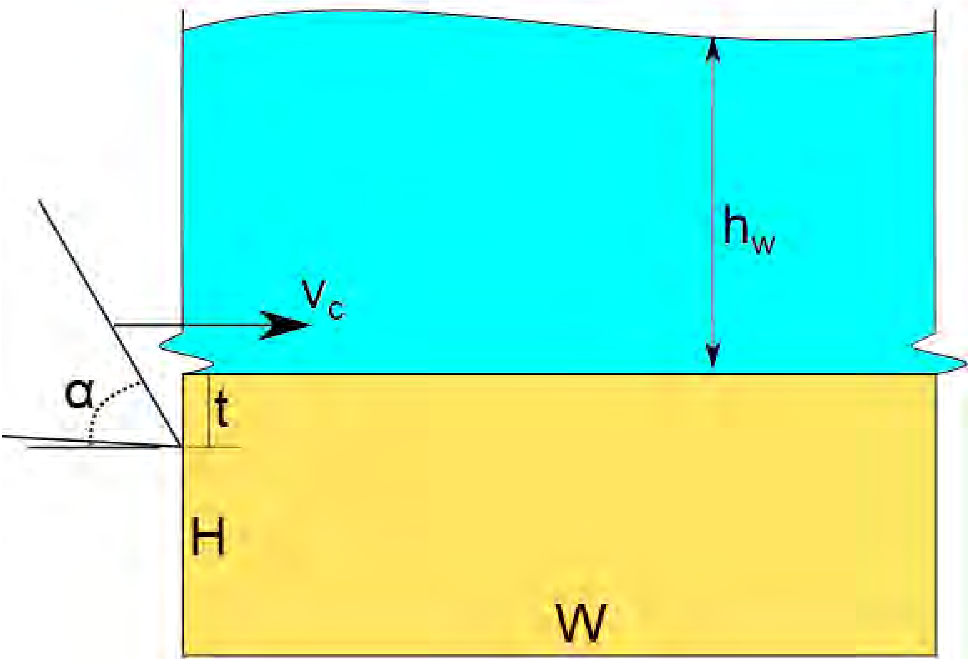
Linear cutting

Comparison of DEM-SP with experimental results of Alvarez Grima et al.[3]

- Range hydrostatic pressure:
  1-180 bar
- Range cutting velocity:
  0.02-2 m/s
- Limestone



Linear cutting: Simulation setup



Geometry

H = 0.1 m

W = 0.35 m

v_c = 1 m/s

t_c = 0.02 m

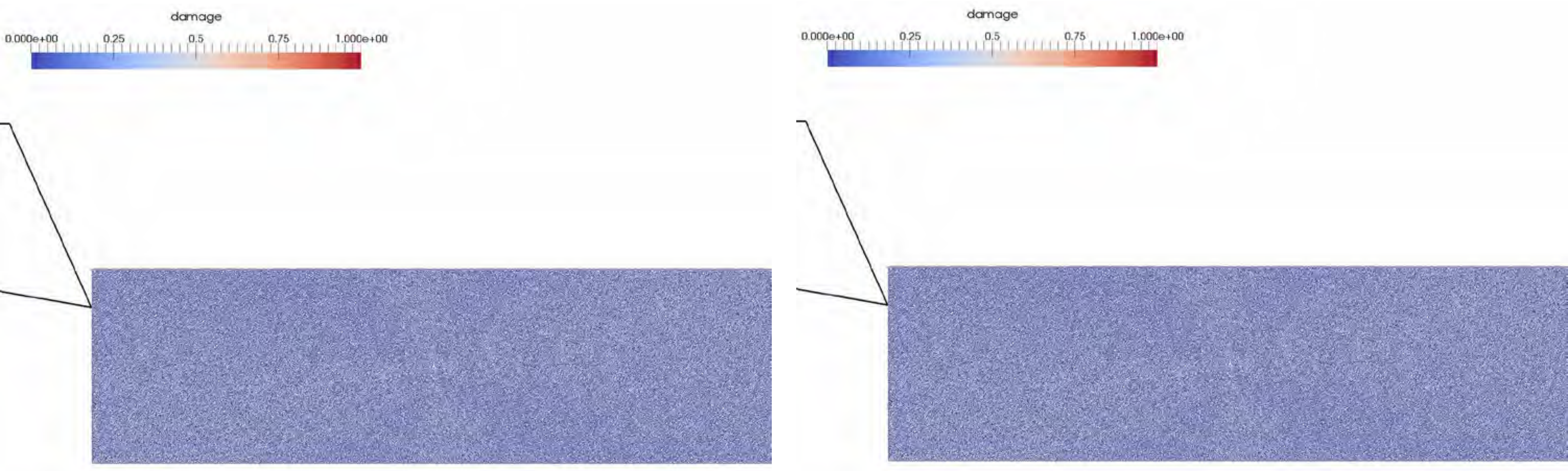
α = 68 °

h_w = 0-2000 m

Material	Alvarez Grima et al	DEM-SP
σ_{UCS} [MPa]	7.92-10.64	9.89
σ_{BTS} [MPa]	0.86-1.15	1.47
E [GPa]	5.95-9.98	8.03
ν [-]	0.23-0.33	0.28

Linear cutting: Results

Atmospheric vs hyperbaric (2km)



Damage: $\frac{\#broken\ bonds}{\#initial\ bonds}$

Slowed down by 50x

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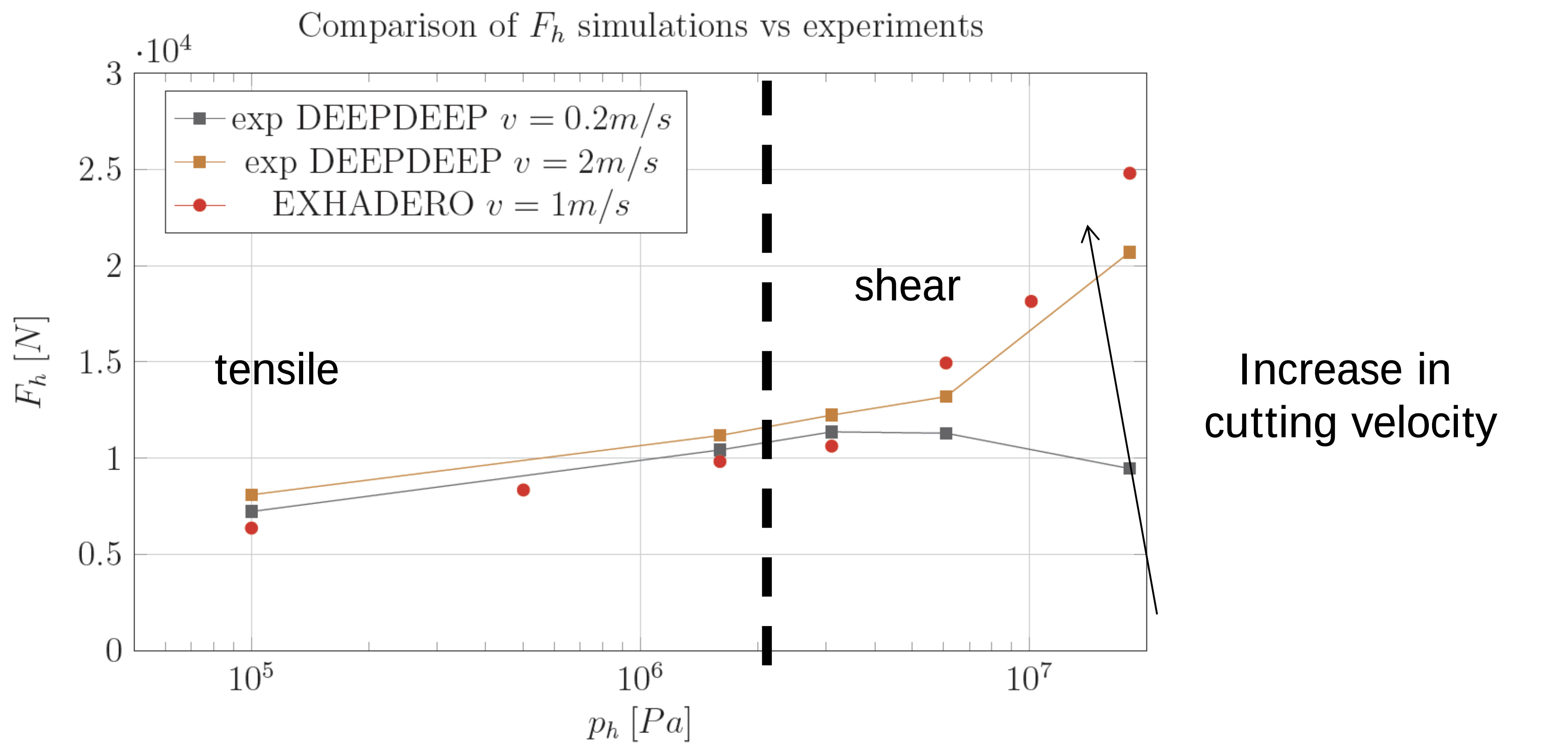
Linear cutting: Results

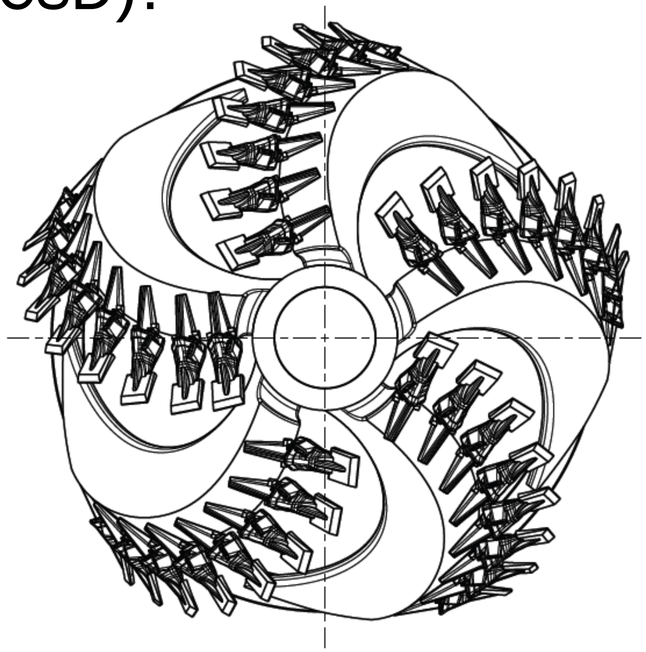
Comparison experimental results from Alvarez Grima et al[3]



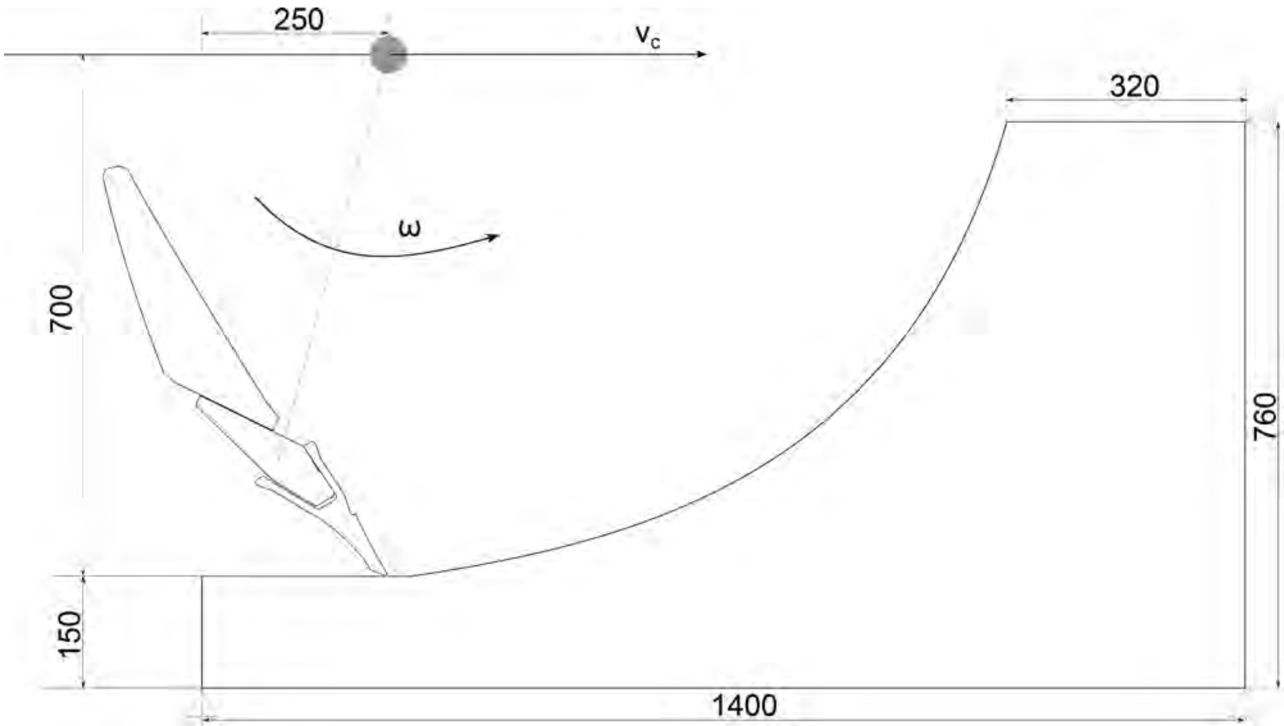
Circular cutting

Current engineering practice based on purely linear cutting tests, while in circular cutting (CSD):

- $t_c \neq$ constant
- $v_c \neq$ parallel to rock bed
- $F_c \neq f(c_1 t_c)$



Circular cutting: Setup



v_c = 0.2 m/s

ω = 1.62 rad/s

α = 60 °

h_w = 0-30 m

Material	DEM-SP
σ_{UCS} [MPa]	20
σ_{BTS} [MPa]	3
E [GPa]	5

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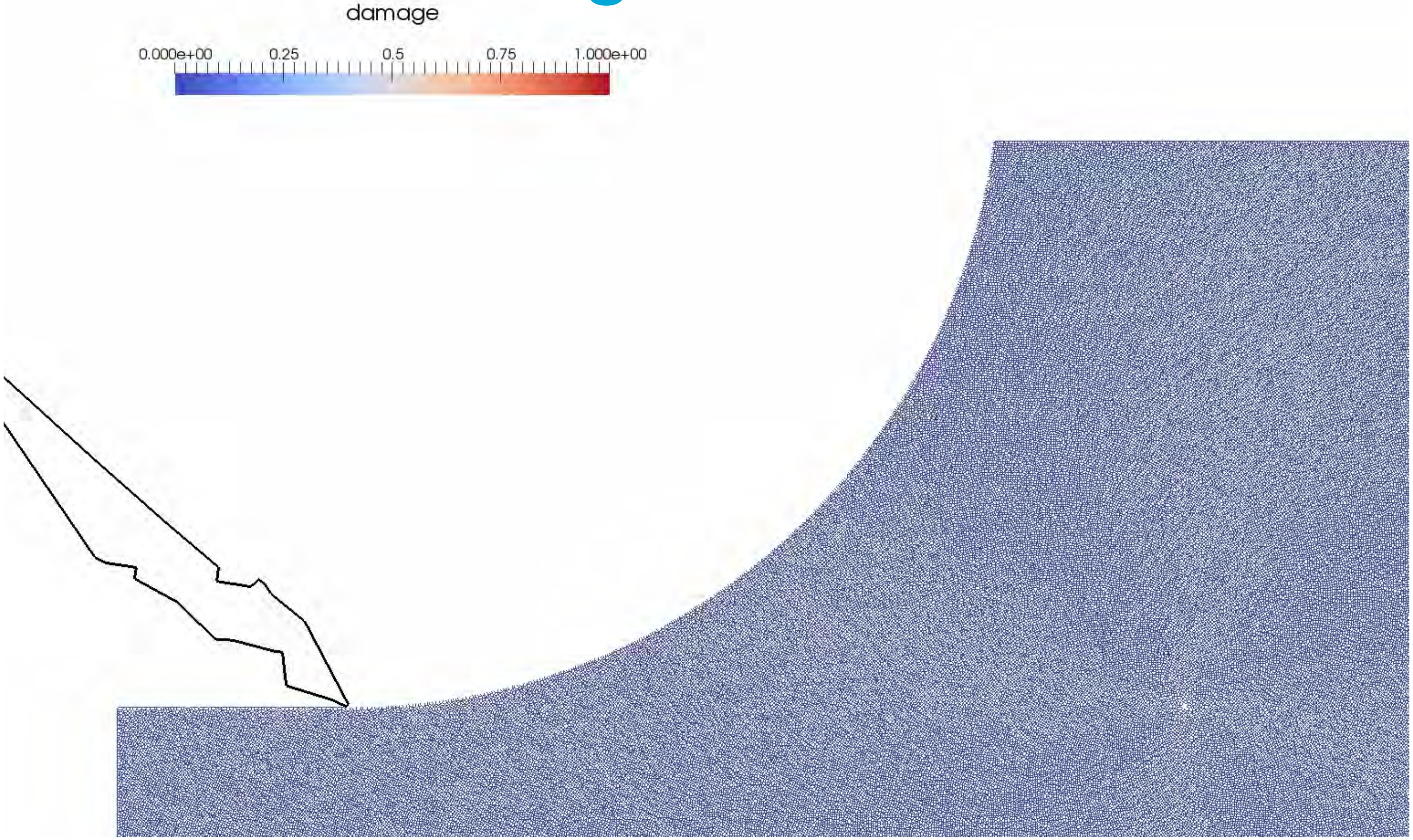
Circular cutting: Results



Damage: $\frac{\#_{broken\ bonds}}{\#_{initial\ bonds}}$

Slowed down by 16x

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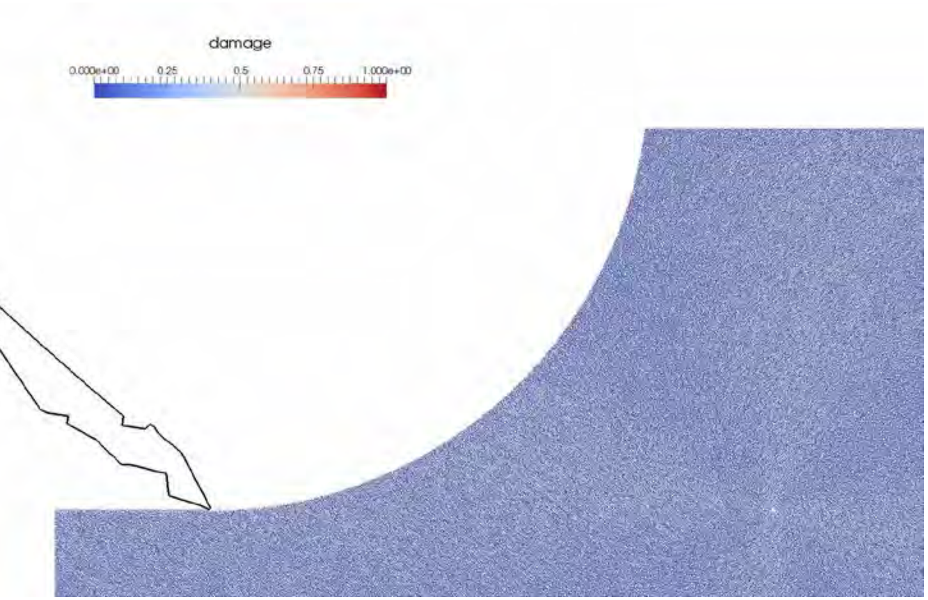
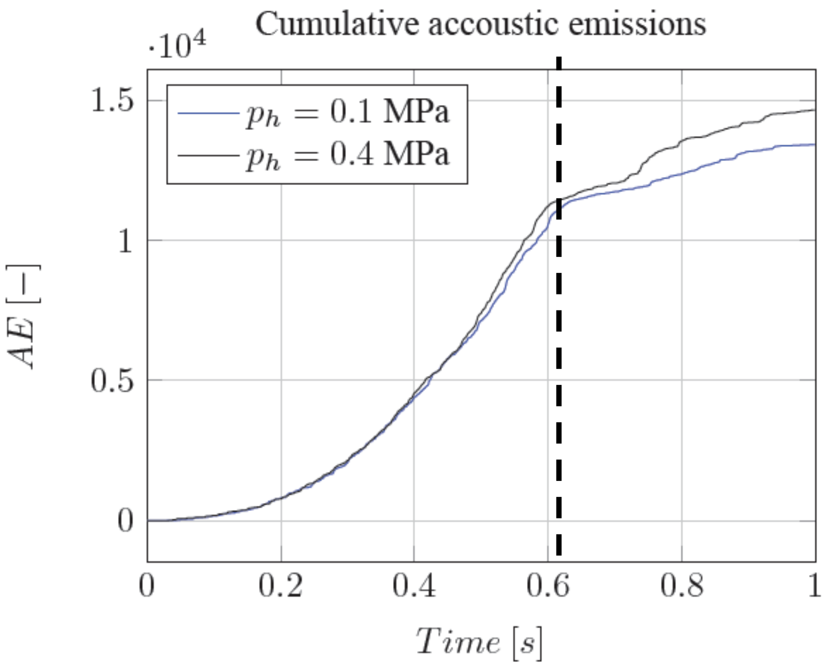
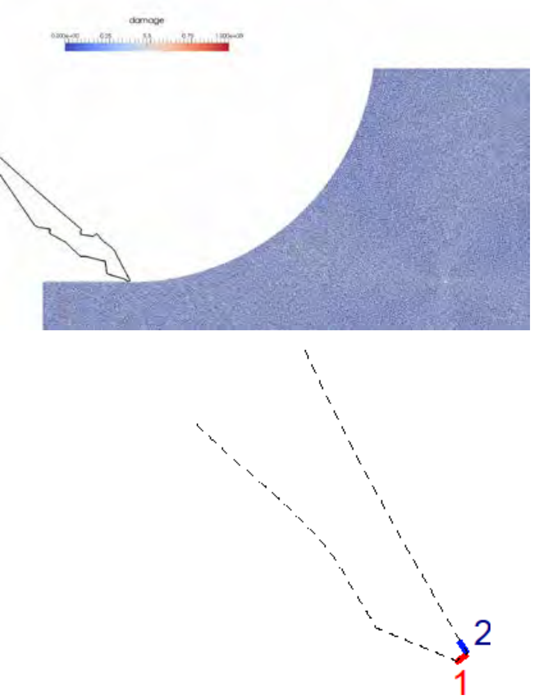
Circular cutting: Results

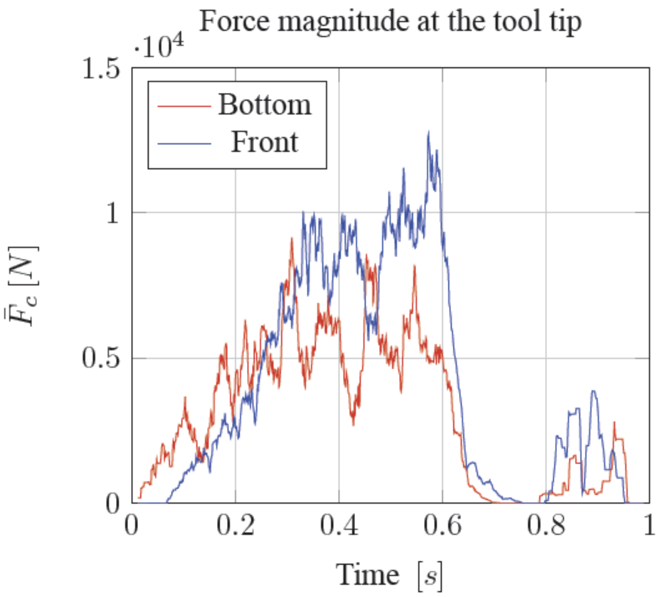


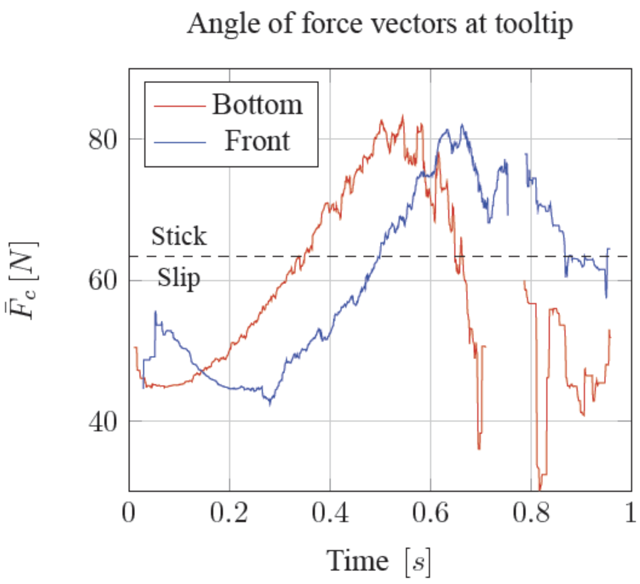


- Three regimes
- 5% increase in required energy measured

Circular cutting: Results







- Transition in wear mechanism
- Wear flat (1): significant influence on cutting force

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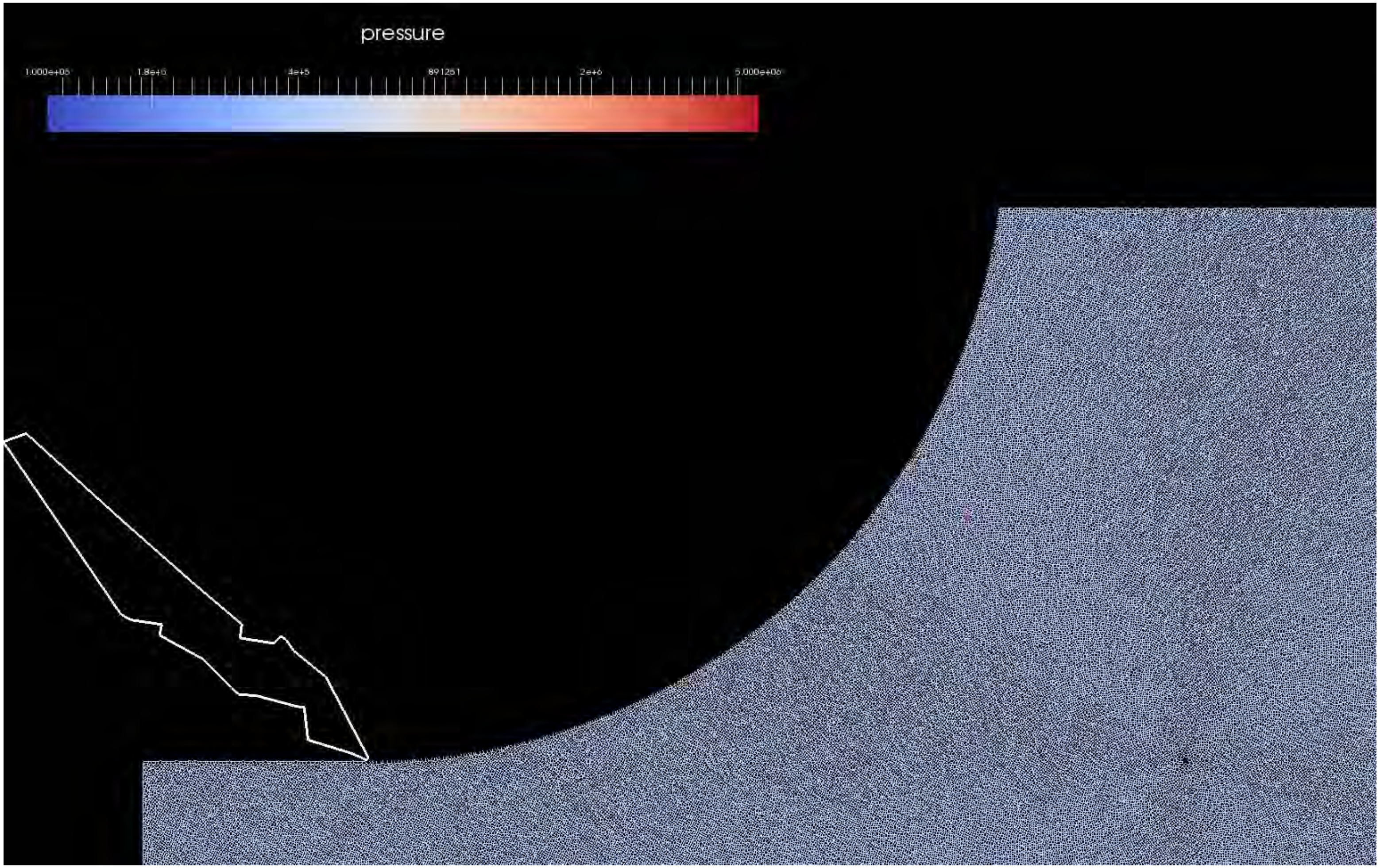
Circular cutting: Results



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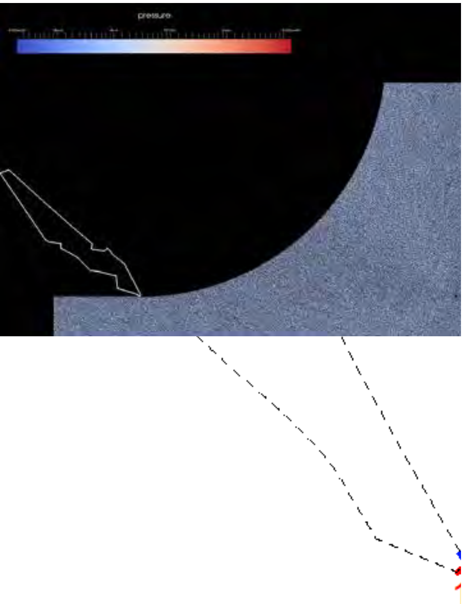
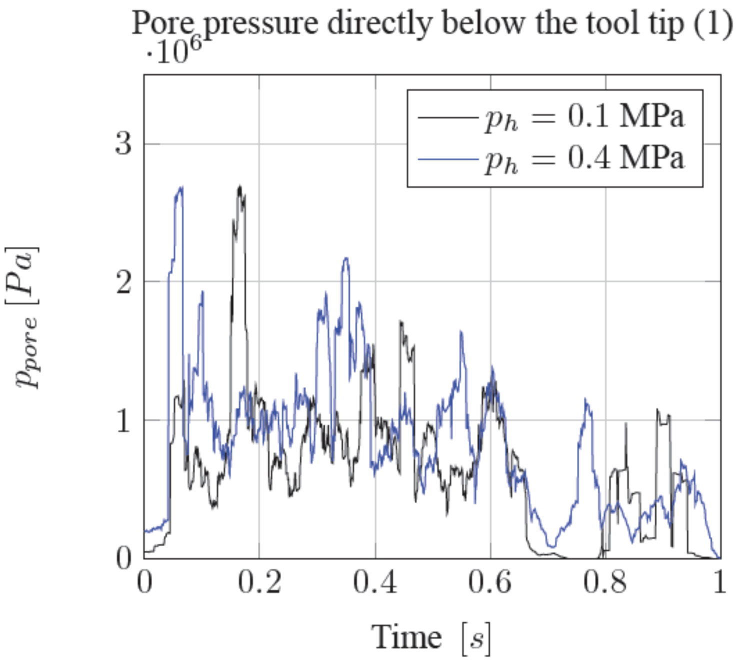
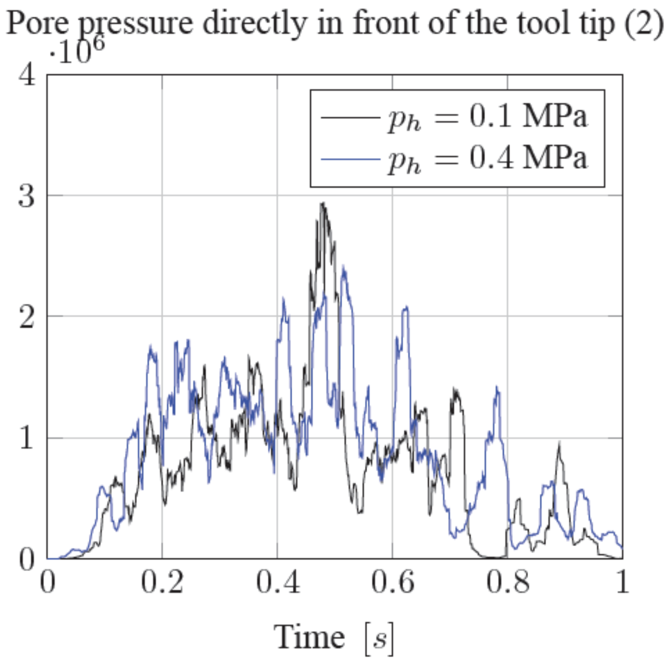
Circular cutting: Results







Time averaged difference approx 10%

Conclusions

- Simulations correspond well with experiments
- Larger water depths lead to higher cutting forces
- Size of the crushed zone increases with water depth

- Transition in cutting modes: scratching, brittle and edge chipping
- Transition in wear mechanisms

Although still in 2D, the methodology is able to capture the relevant processes for simulation of rock cutting

Thank you for your attention

Subsidy program

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Ministerie van Economische Zaken, Landbouw en Innovatie

Industrial partners

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For more info, see:

1. Helmons, R.L.J., Miedema, S.A., van Rhee, C. (2016). Simulating hydro mechanical effects in rock deformation by combination of the discrete element method and the smoothed particle method. *International Journal of Rock Mechanics and Mining Sciences 86, 224-234*

2. Helmons, R.L.J., Miedema, S.A., Alvarez Grima, M., van Rhee, C. Modeling fluid pressure effects when cutting saturated rock, *Engineering Geology*, **accepted**.

Or other my other publications on researchgate.net: Rudy Helmons