LS-DYNA for Mining and Mineral Processing Applications

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Outline

- Rock drilling
- Stirred media mill

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Discrete Element Method

- Rigid spheres and Newton's second law

$$m_i \frac{d\boldsymbol{v}_i}{dt} = \boldsymbol{F_i}^{ext} + \sum_{j=1}^{n_j} \boldsymbol{F}_{ij}$$

- Penalty based contact
  - Normal and shear stiffness
- Friction
- Normal and shear damping

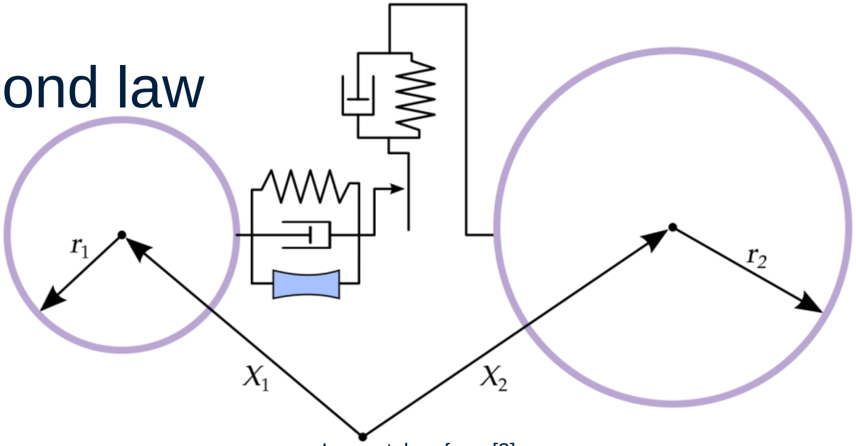
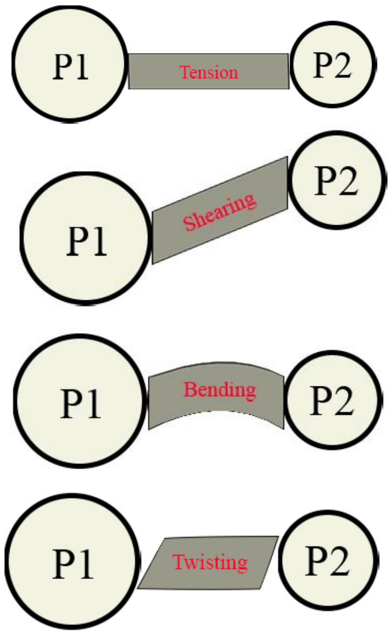


Image taken from [2]

[1] Cundall, P.A. and O.D.L. Strack (1979). A discrete numerical model for granular assemblies.
[2] Livermore Software Technology (2021). LS-Dyna Keyword User's Manual Volume 1 (R12)

Bonded Discrete Element Method



- Linear elastic beams connects spheres
- For each bond:
  - Normal and shear stiffness
  - Normal and shear strength

$$\Delta \bar{F}^n = \bar{k}^n A \Delta U^n$$
$$\Delta \bar{F}^s = -\bar{k}^s A \Delta U^s$$
$$\Delta \bar{M}^n = -\bar{k}^s J \Delta \theta^n$$
$$\Delta \bar{M}^s = -\bar{k}^n I \Delta \theta^s$$

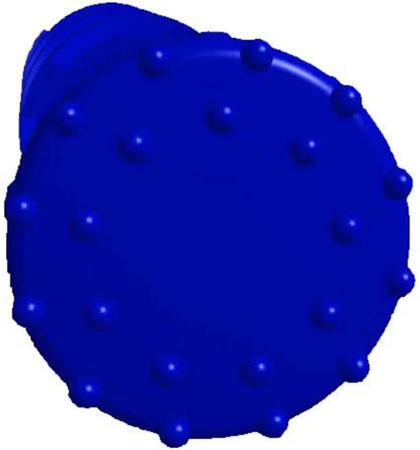
- Bond breaks once prescribed strength is exceeded

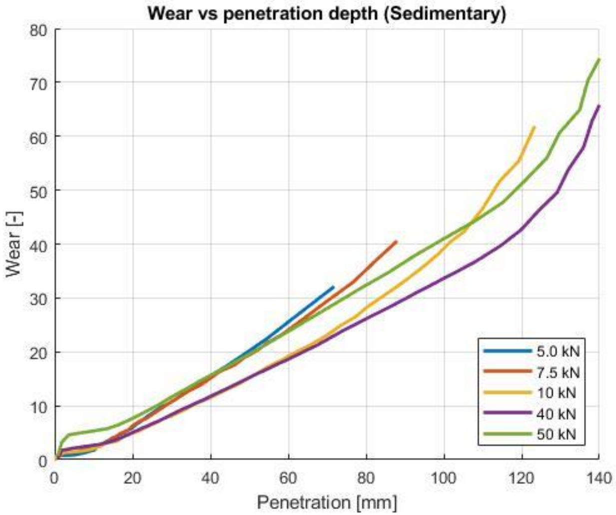
$$\bar{\sigma}^{\max} = \frac{-\bar{F}^n}{A} + \frac{\left|\bar{M}^s\right| \bar{R}}{I} \geq \sigma_c$$
$$\bar{\tau}^{\max} = \frac{\left|\bar{F}^s\right|}{A} + \frac{\left|\bar{M}^n\right| \bar{R}}{J} \geq \tau_c$$

[3] Potyondy, D., Cundall, P (2004). A bonded-particle model for rock.

BDEM and rock drilling

GEOFIT
SMART GEOTHERMAL





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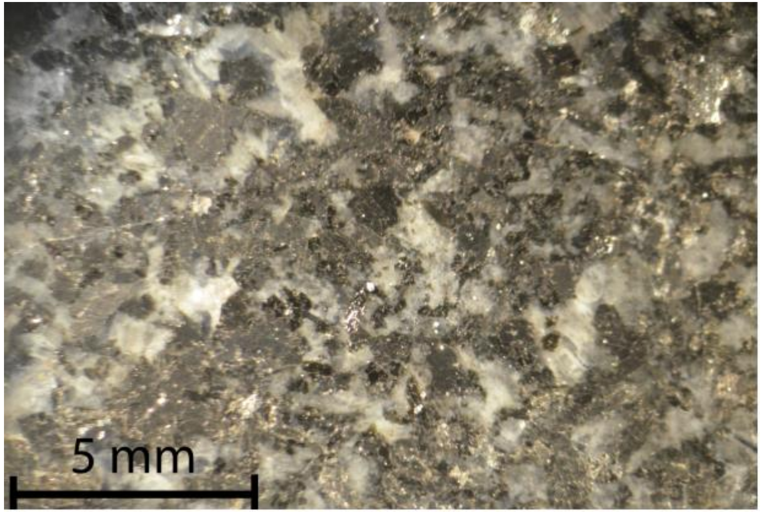
Rock materials

- Rock materials are heterogeneous
  - Different types of minerals
  - Varying grain sizes, shapes, boundaries and orientations

- Unpredictable material
  - Crack initiation and propagation

- How to model numerically?



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Heterogeneous rock model

Three steps in generating a rock body

1. Generation of grains with irregular sizes and shapes

2. Assigning BDEM properties of the grains

3. Cementing grains together

Computational Particle Mechanics
https://doi.org/10.1007/s40571-021-00434-w

A statistical DEM approach for modelling heterogeneous brittle materials

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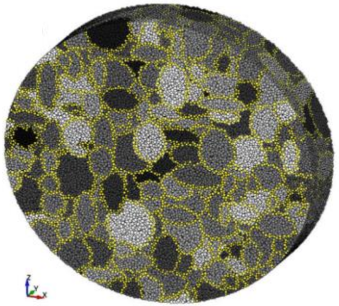
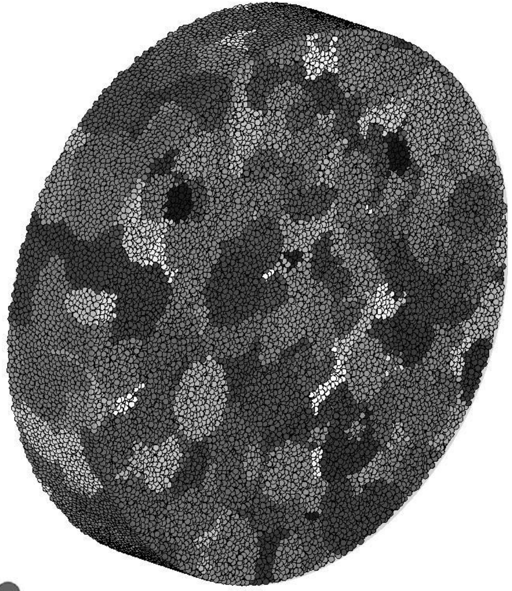
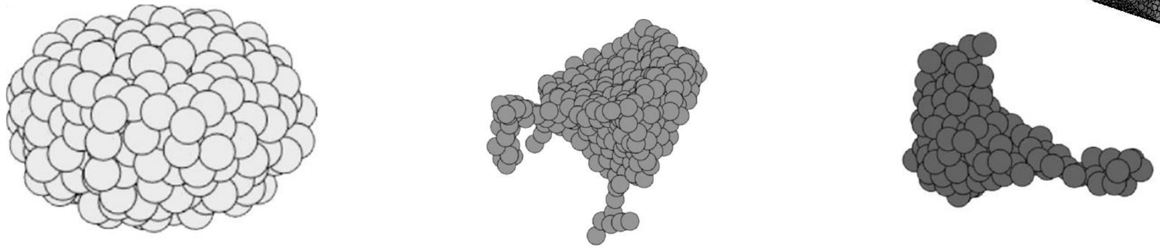


Heterogeneous rock model: Grain generation

1. Grains are represented by randomized ellipsoidal subsets of Bonded DEM
   - Uniform statistical distribution of ellipsoidal radii:

$$R_x, R_y, R_z \sim U(R_{\min}, R_{\max})$$



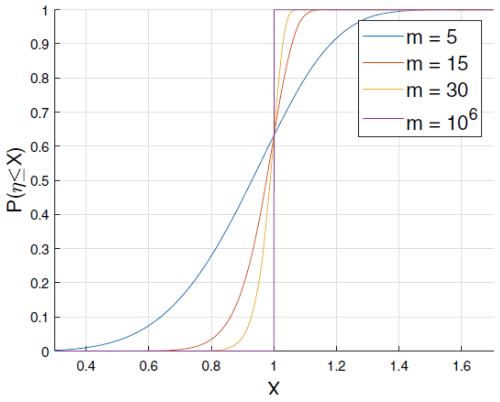


Heterogeneous rock model: Grain properties

2. The **mean** bond stiffnesses and strengths of each grain is given by the Weibull distribution

$$f(\eta, \eta_0, m) = \frac{m}{\eta_0}\left(\frac{\eta}{\eta_0}\right)^{m-1} e^{-(\eta/\eta_0)^m}$$

where m is the heterogeneity index



- Bond properties within one grain is allowed to vary within +/- 10 % of the mean value

Color represents mean grain strength

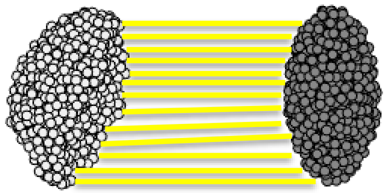
Heterogeneous rock model: Cementing

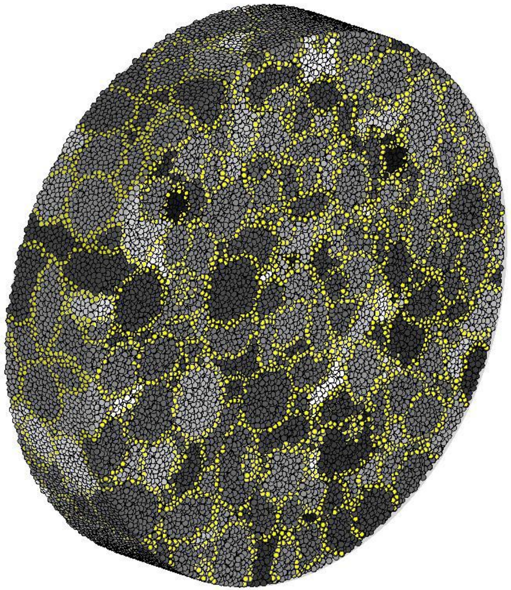
3. A grain is cemented together with its neighbours with down-scaled bond strengths

$$\bar{\sigma}_c^{ij} = C_f \cdot \bar{\sigma}_c^i$$

$$\bar{\tau}_c^{ij} = C_f \cdot \bar{\tau}_c^i$$

Grain i Grain j



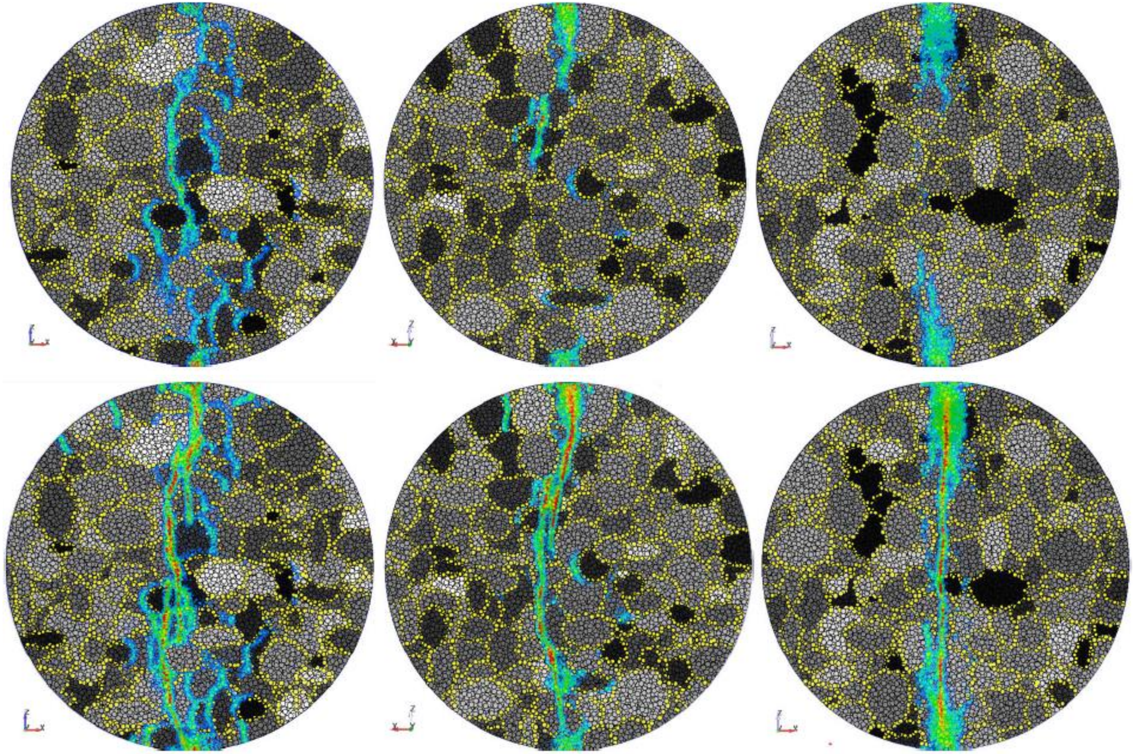


Results: crack propagation

Boundaries | Boundaries/grains | Grains

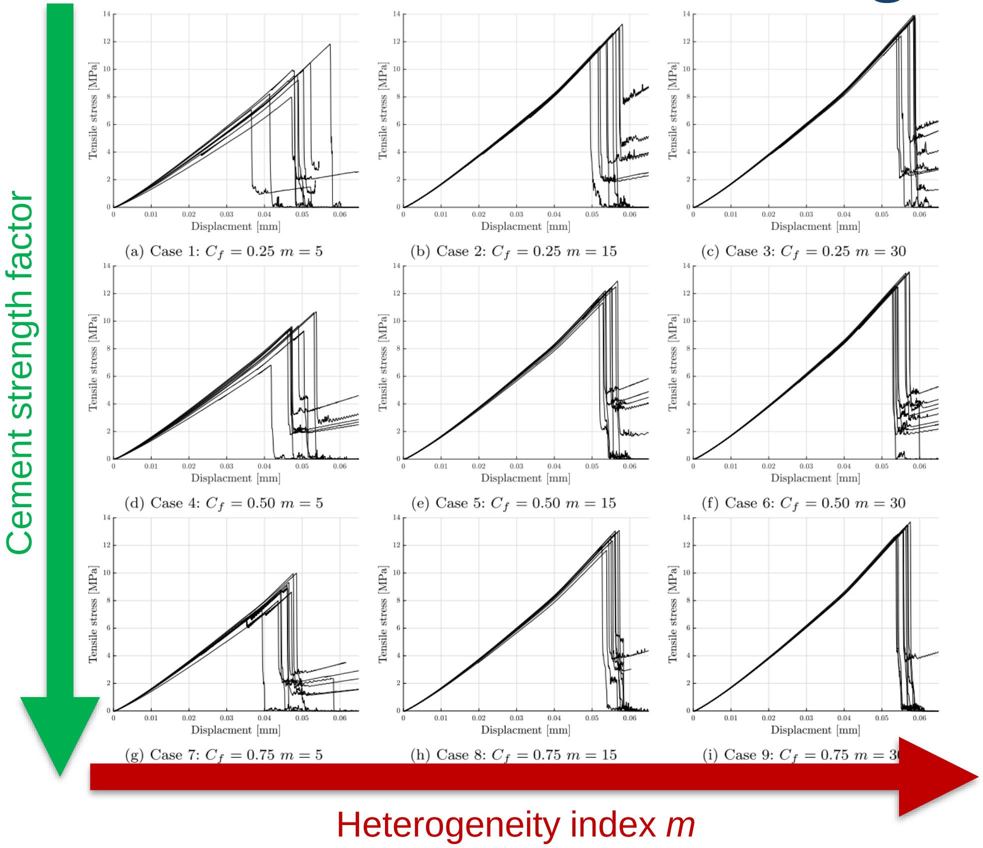
Before main fracture

After main fracture



C_F=0.25 | C_F=0.50 | C_F=0.75

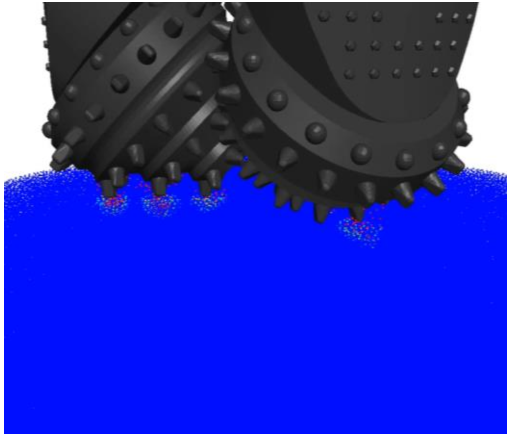
Predicted tensile strength



Variation increases with decreased cement strength and heterogeinity index

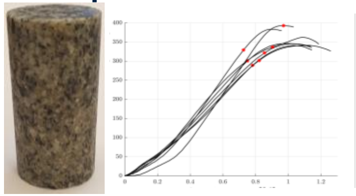
$$\sigma_t = \frac{2F}{\pi D t}$$

Ongoing work: DigiRock

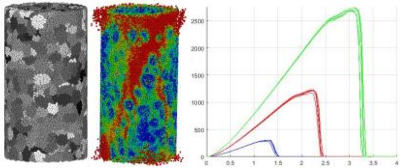


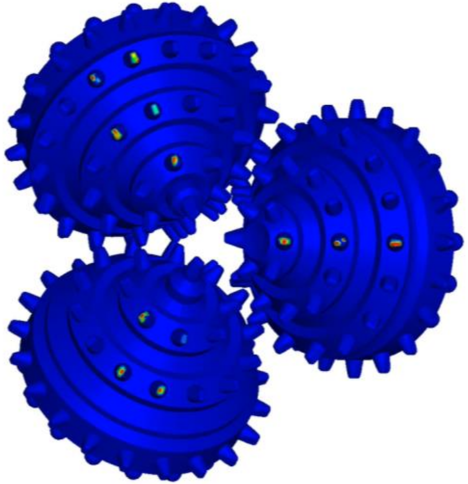
Aim: Develop efficient and physically realistic numerical models for study and optimization of rock drilling

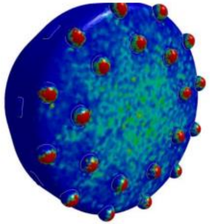
Experimental data

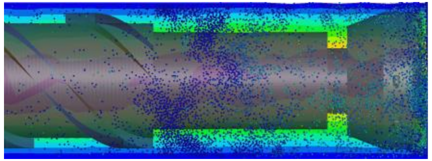


Calibrate rock model









Wear modelling

Fluid dynamics

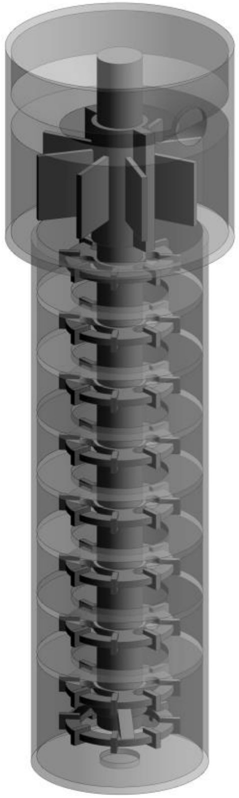
Stirred media mill

- Comminution in the minerals industry
  - Tumbling mills, low energy efficiency
  - **Stirred media mills**, higher energy efficiency
- Optimization of comminution in stirred media mills
- Modelling a wet-operating stirred media mill
  - Multiphysics in a complex system

Materials

Pilot wet stirred media mill

- Outotec HIG5
  - 7.5 kW
  - 6.2 l
  - 240 l/h



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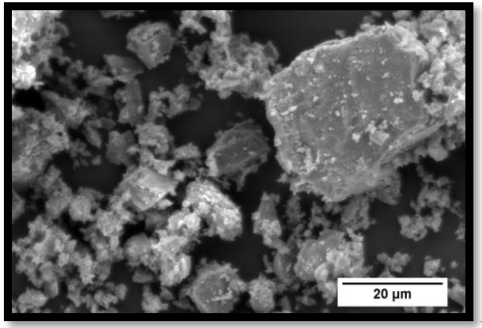
Materials

Grinding beads and feed material

- Grinding beads
  - Composite alumina and zirconia ceramic
  - Spherical, 2.0 - 4.0 mm

- Feed material
  - Mineral powder + water
  - 46 % solids by weight



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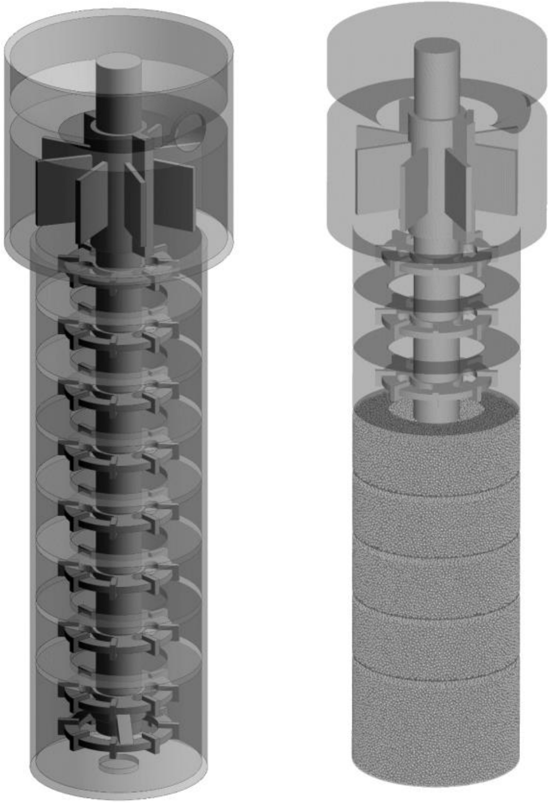
Modelling

- FE-model
- DEM for grinding media
- Penalty-based coupled DEM-FEM



Modelling

Slurry

Incompressible Computational Fluid Dynamics (ICFD)

- Governing equations

$$\rho\left(\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}\right)=-\frac{\partial p}{\partial x_i}+\mu\frac{\partial^2 u_i}{\partial x_j \partial x_j}+\rho f_i$$

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=0$$

$$\frac{\partial u_i}{\partial x_i}=0$$

- Model input
  - Constitutive model

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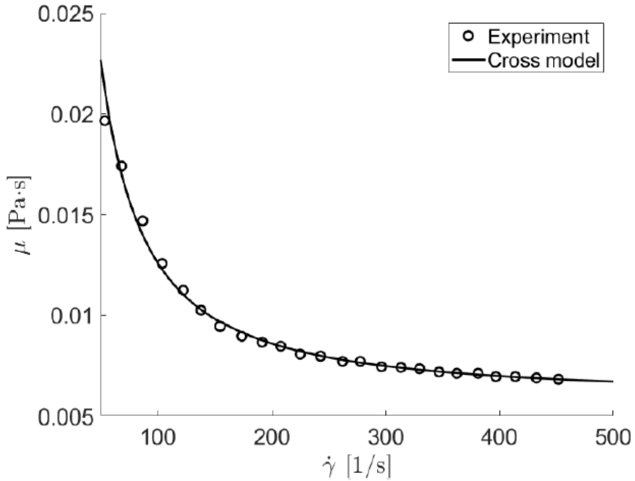
Modelling

Slurry

Constitutive model

- Newtonian/non-Newtonian?
  - Rheology suggests non-Newtonian
- Shear-thinning (Cross, 1965)



$$\mu = \mu_\infty + \frac{\mu_0 - \mu_\infty}{1 + (\lambda\dot{\gamma})^n}$$

Cross, M. M. (1965). Rheology of non-Newtonian fluids: A new flow equation for pseudoplastic systems. *Journal of Colloid Science*, **20**, 417-437

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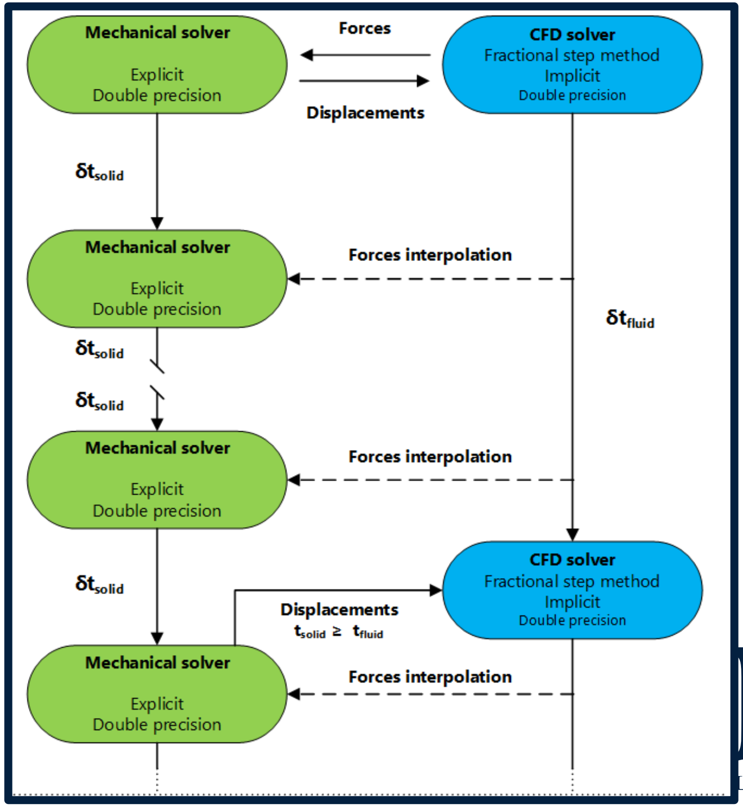
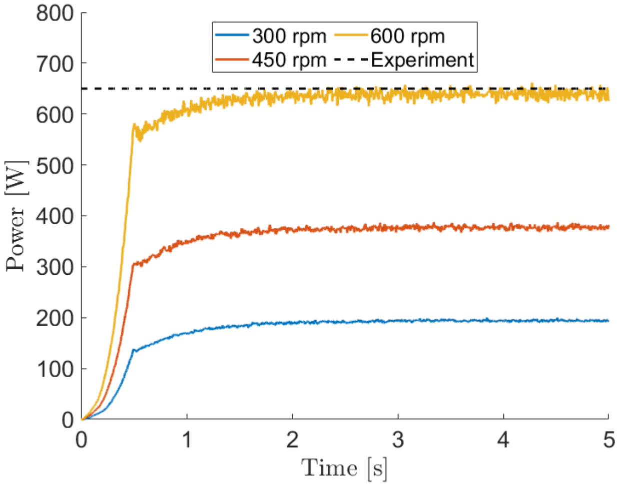
Modelling

Coupled ICFD-DEM-FEM

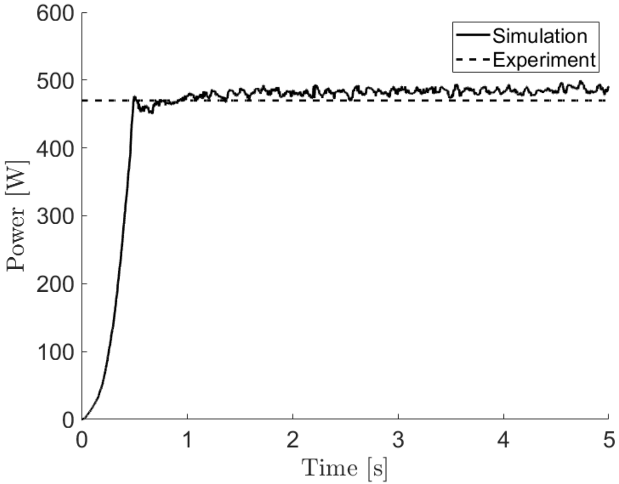
- Partitioned approach
- Loosely coupled
- Two-way coupling
- Drag force



Modelling



Water



Mineral slurry

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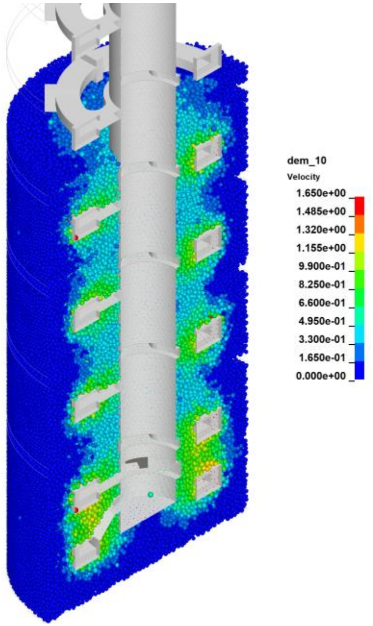
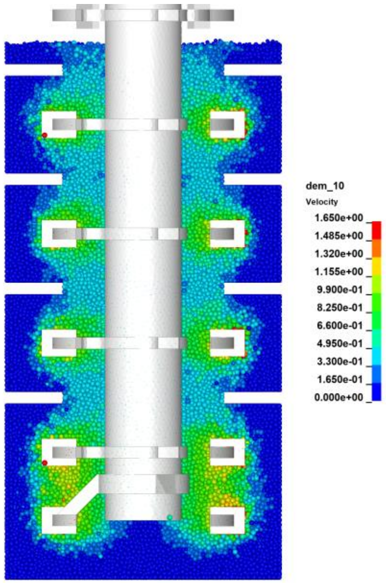
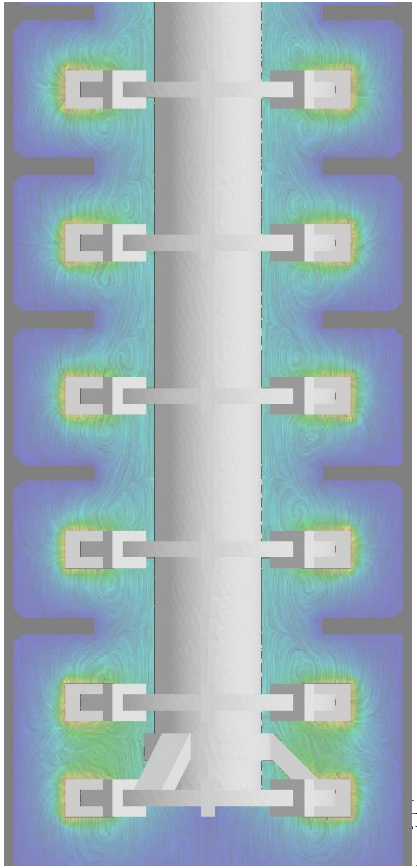
Modelling

Grinding media and slurry dynamics

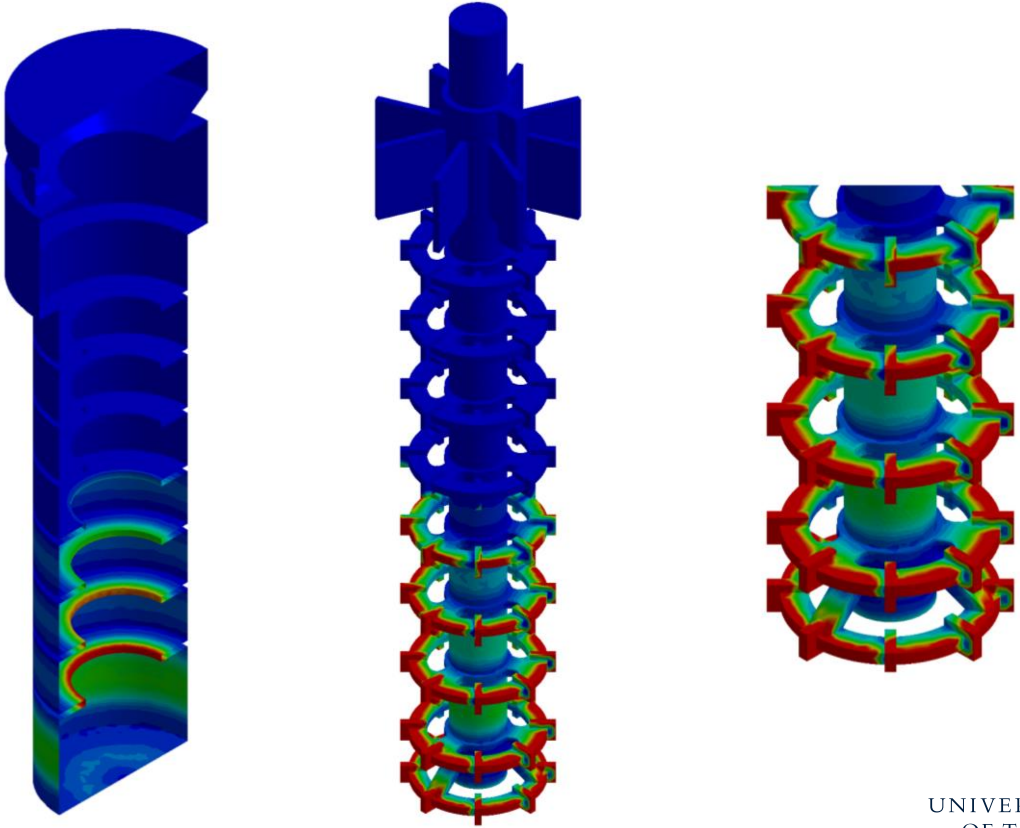






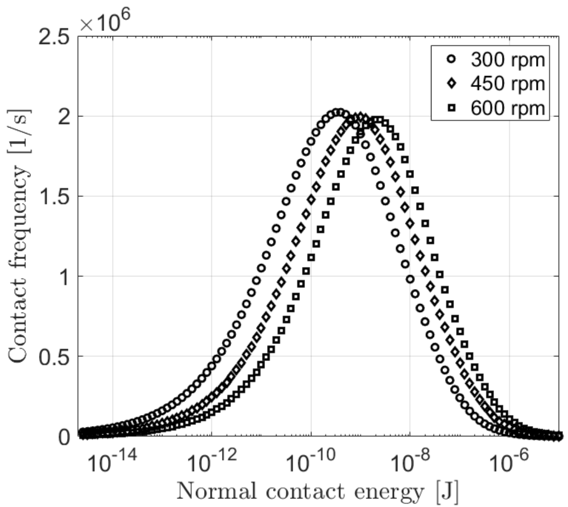
Modelling

Wear

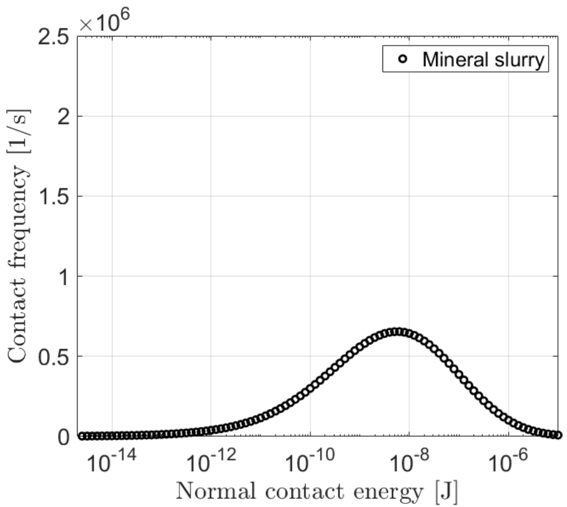


Modelling

Contact energy spectra



Water



Mineral slurry

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Conclusions

- Statistical rock model
  - Crack initiation, propagation and coalescence
  - Applicable in rock drilling
- Coupled ICFD-FEM-DEM models
  - Dynamics of grinding media and slurry
  - Power draw and wear
  - Interparticle collisions
  - Quantification of the comminution performance

Questions

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