Hydraulic transmissivity of fracture networks generated through geomechanical fracture-growth simulations

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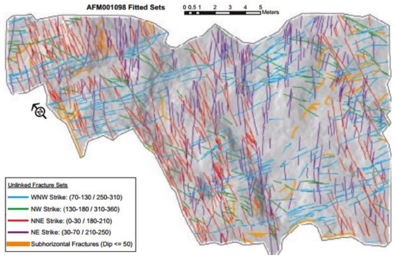
1. Description of problem

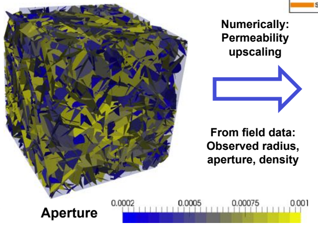
In all formation types, particularly crystalline rock, evaluating flow in fractured rock is vital to ensuring that the geological barrier is sufficient to isolate radionuclides from the environment. In rock with extremely low permeability, the vast majority of transport occurs in natural fracture networks, which are difficult to characterise due to complex network connectivity, fracture morphology, and anisotropy.

Many authors have approached this problem by simulating fluid flow through stochastically generated fracture networks. The network characteristics (fracture radius, aperture, density, connectivity) of many simulations are correlated to the resulting permeability to find how they are related.

We seeks to inject more realism into this process by inserting geomechanical effects into networks by modelling growth with a fracture mechanics simulator.



Fracture outcrop in Forsmark, Sweden, divided into sets by dip and strike. Analysed as part of a characterisation study by Stephens et al. (2007) for siting a geological repository for radioactive waste.



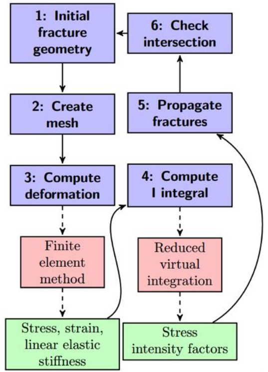
Discrete fracture network modelling with a network of randomly oriented fractures. Disk colours show fracture apertures.

Effective permeability tensor

$$\boldsymbol{k} = \begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{bmatrix}$$

The eigenvectors of the tensor provide the maximum and minimum directions of flow in the rock mass.

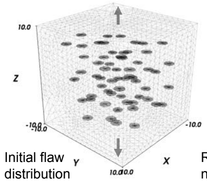
2. Mechanical model workflow



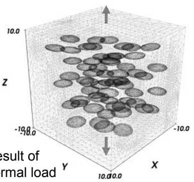
Mechanical workflow.

The Imperial College Geomechanics Toolkit (ICGT) is a finite element based fracture mechanics simulator, capable of modelling fracture growth, flow, and effective permeability (Paluszny & Zimmerman 2013). The model is seeded with initial elliptical flaws, a load is applied, and fractures propagate quasi-statically in growth stages.

Along the fracture tip, stress intensity factors (SIFs) are calculated, measuring the energy concentrated at the fault tip in different fracture opening modes. These are used to evaluate failure criteria, creating a growth vector that extends the fracture.



Initial flaw distribution



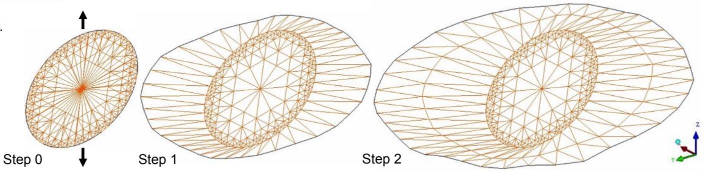
Result of normal load

Propagation criteria

Failure: sub-critical crack growth (Atkinson 1984)

Length: Paris law (Paris & Erdogan 1963)

Angle: Richard (2004)



Growth of an 1 metre radius isolated flaw, oriented 45° to the load direction. The new surface is created by connecting the growth vectors.

3. Advancements in geomechanical fracture growth modelling

Hybrid stress intensity factor computation

Our model has two methods available for calculate the SIFs: virtual disk integration and displacement correlation (Nejati at al. 2015). The former is used by default, unless the integrating disk would intersect another nearby fracture.

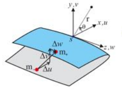
Quarter point elements along fracture tip

Moving the mid-side nodes of the finite elements at the crack tip leads to a better approximation of the stress singularity.

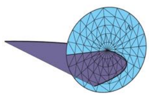
Geomechanical fracture apertures

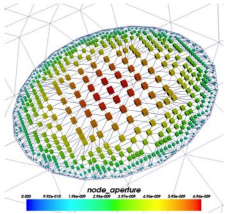
Fracture apertures are determined from the mesh separation between fracture surfaces, honouring stress equilibrium in the model.

Displacement Correlation (DC)

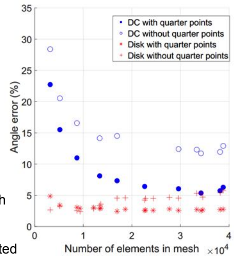


Virtual disk integration





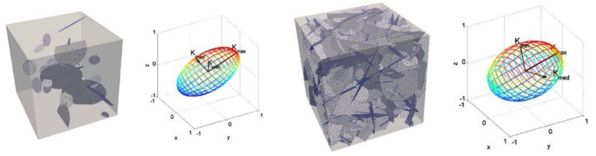
Fracture plane with aperture variation represented using coloured glyphs.



Comparison between SIF calculation methods, by comparing mesh density to the error in the computed propagation angle.

4. Permeability calculation

To characterise the transport properties of a volume containing a fracture network, a permeability upscaling method has been implemented (Lang et al. 2014). By element-wise averaging the pressure and flux, and inverting for the permeability, we calculate a tensor that describes the permeability in different directions.

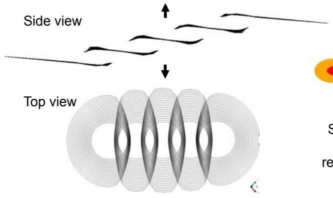


Permeability upscaling demonstrated on anisotropic fractured volumes (Lang et al. 2014). The tensor is represented as a 3D spheroid.

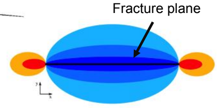
5. Discussion and future insights

Geomechanically-generated networks with realistic apertures have been show in 2D to yield lower permeabilities than do stochastic networks. By including the effects of fracture coalescence, we will further constrain the impact of geomechanics on network permeability in 3D.

Interaction between fractures is quantified using SIFs. This approach is relatively unexplored, and can help constrain the point when fractures begin to interact, and the effect this will have on the resulting geometry.



An array of five fractures after 20 steps. Each curve shows the fracture front at each step.



Stress concentration around an isolated fracture. Red colours represent increased stress. Blue colours represent shadowing. These zones control how fracture geometry changes once interaction begins.

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Acknowledgements

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Society of Petroleum Engineers, London Monthly Meeting, 28 May 2019