Investigating the Relative Permeability of Coal Fractures Using Stochastic Analysis and High-Fidelity Computational Modelling

Dmytro Sashko[1], Dr Travis Mitchell[2], Łukasz Łaniewski-Wołłk[1,2], A/Prof Christopher Leonardi[1,2]

[1] School of Mechanical and Mining Engineering, The University of Queensland, St Lucia, QLD, Australia
[2] Institute of Aeronautics and Applied Mechanics, Warsaw University of Technology, Warsaw, Poland

Introduction

The absolute and relative permeability of a coal seam are key to production outcomes, including gas and water rates and reservoir compaction and subsidence. Contemporary model predictions typically use parameters sourced from downhole diagnostic tests and production history matching. However, this homogenises the influence of the cleat and fracture network, which is complex and somewhat random in nature. The concept of complementary relative permeability curves which smoothly vary with changing saturation has also been shown to be invalid in experimental and numerical studies. The variability and uncertainty associated with important modelling parameters translates to uncertainty in economic and environmental issues.

The aim of this research program is to develop next-generation analysis tools to predict two-phase flow at industry relevant scales in the subsurface, using stochastic analysis and upscaling of high-fidelity models of fracture flow.

Method

The work focuses on the first stage of analysis, namely high-fidelity modelling of two-phase flow in a single fracture.
- The lattice Boltzmann method (LBM) is used to resolve the hydrodynamics of fluid flow in rough fracture geometries.
- The LBM is well-established for use in porous media flows
- A phase-field model is employed to capture the interaction of two immiscible phases (i.e. water and gas), recovering a modified form of the Allen-Cahn equation.
- Recent modifications to the three-phase contact modelling improve the accuracy gas-water interactions at fracture walls

Coal surfaces were imaged using Olympus DSX1000 digital optical microscope to generate roughness data.
- Two different lenses captured wide range of length scales
- An array of 10 x 10 sub-images stitched to create final image
- Power spectrum was extracted using 2D Fourier transform
- Power decay coefficient used to generate synthetic fractures

Pressure gradients are applied to the models which predict fluid velocity, allowing permeability calculation.
- Permeability profile for single roughness and correlation follows a Gaussian distribution across many realisations
- The dependence on roughness of the permeability mean and the standard deviation is non-linear → requires advanced statistical modelling techniques → Generalized additive model for location, scale and shape (GAMLSS)

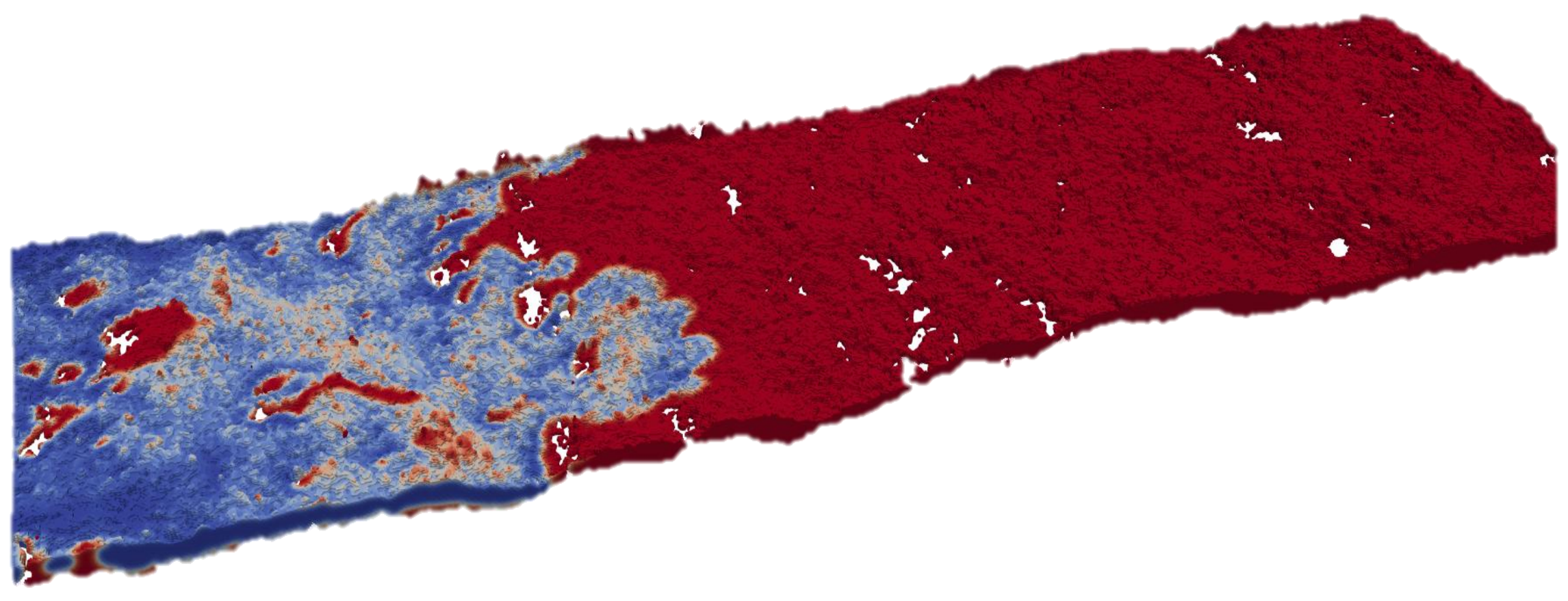

Figure 2: Two-phase LBM simulation of oil displacing water in a CT scan of Berea sandstone fracture for validation purposes. Here blue and red mark oil and water phases correspondingly.

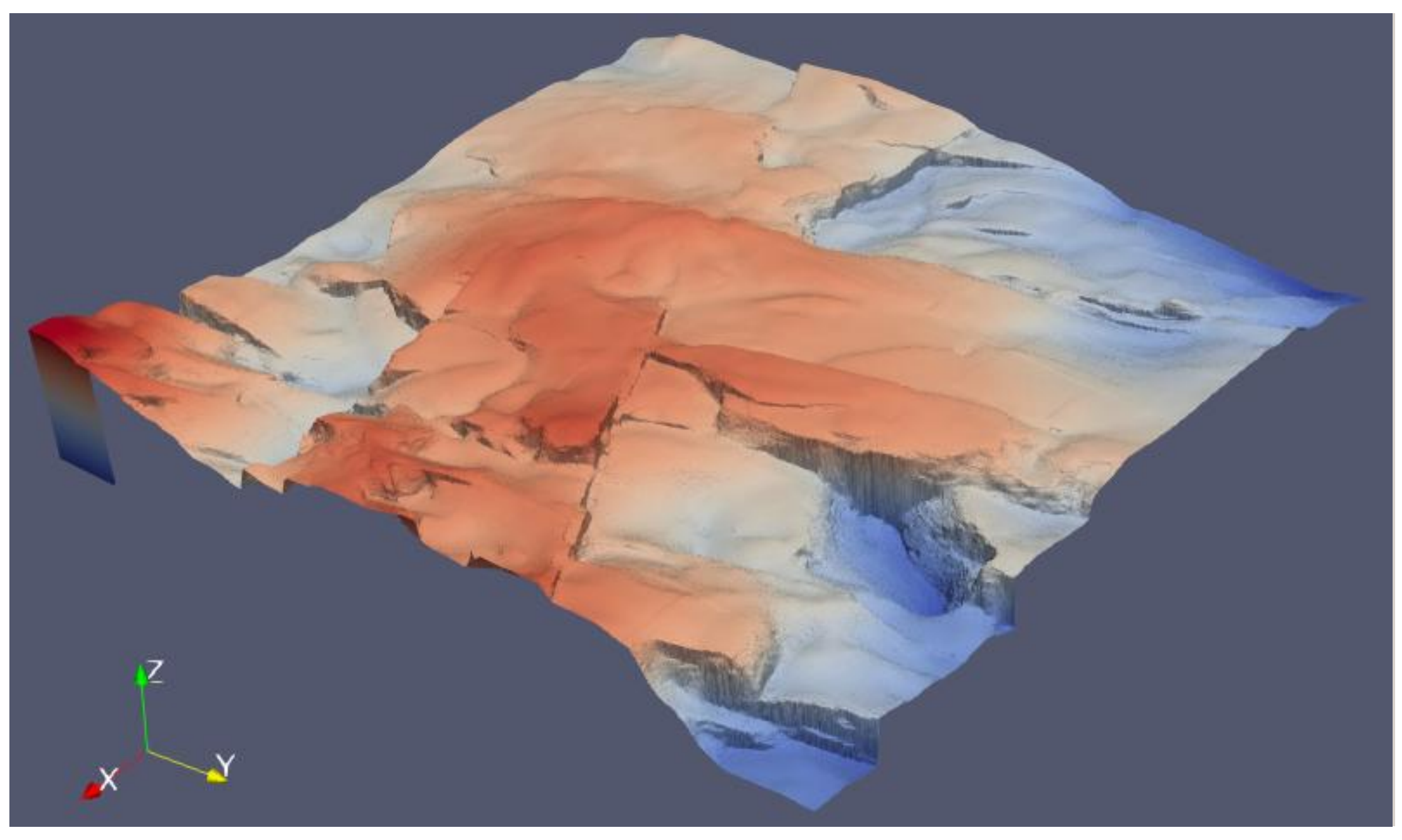

Figure 3: Elevation contour plot of a coal fracture surface obtained using digital optimal microscopy, highlighting smoothness between discontinuities.

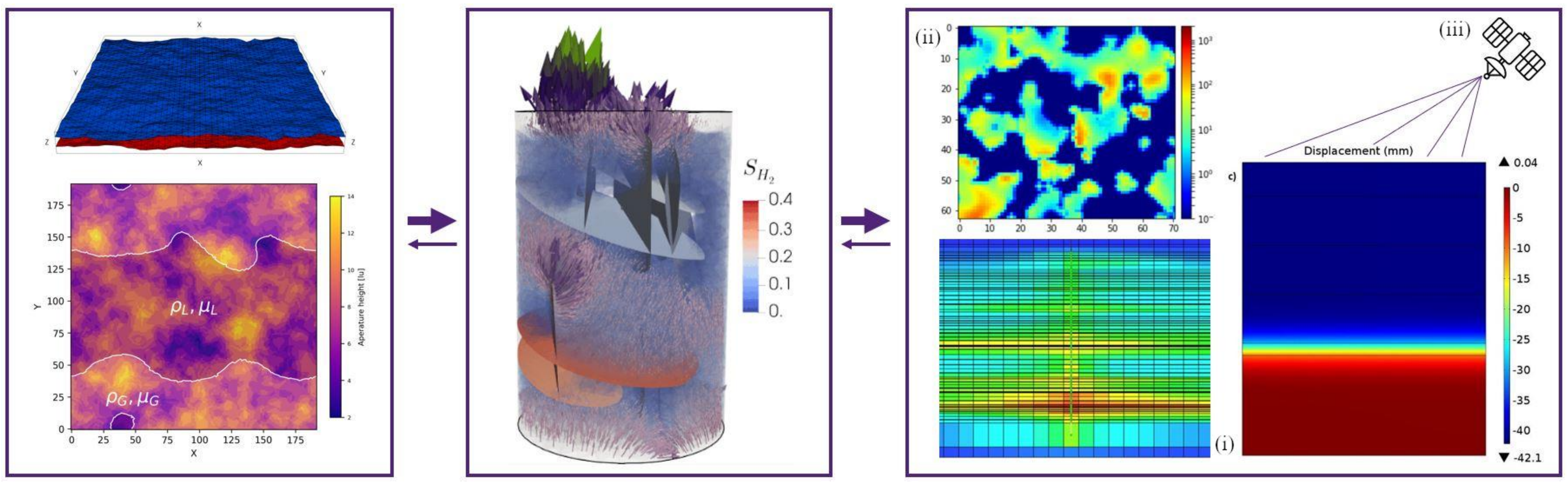

Figure 1: The top-down approach to be taken in this research is focused on analysis at three scales: (1) High-fidelity modelling of two-phase flow in a single fracture using roughness statistics from digital optical microscopy and outputting surrogate model(s) linking flux, pressure and saturation based on hundreds of unique model realisations; (2) Transport in the discrete fracture network (DFN) of a representative elemental volume (REV) using fracture spacing and dispersion statistics from image logs and the surrogate model and statistics of two-phase flow in a single fracture, outputting averaged, orthotropic transport properties and statistics for each REV; (3) Integrated reservoir-geomechanical modelling using REV transport properties for multiple geological units and stratigraphy based on well logs and copula geostatistics, with feedback from production data and surface movement measurements from InSAR.

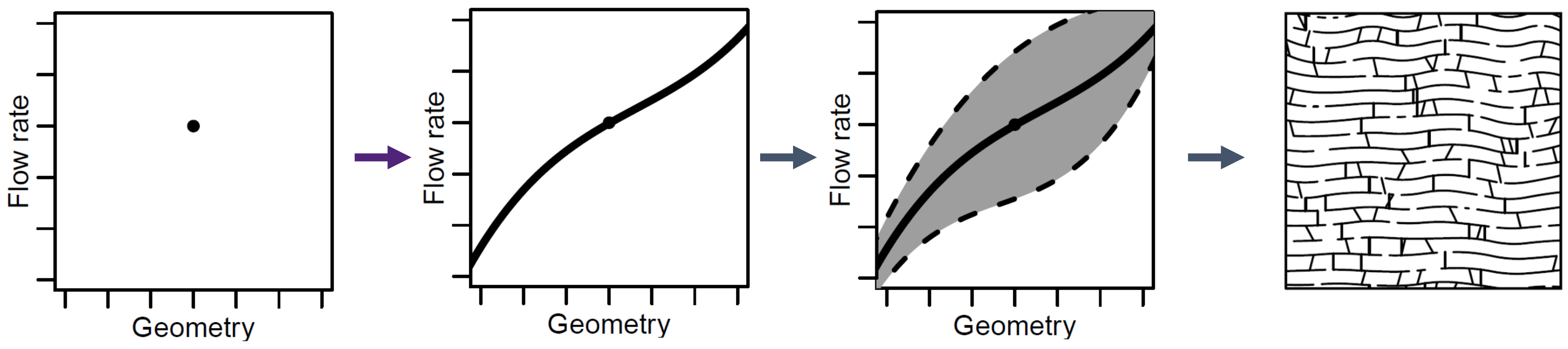

Figure 4: Fractures are rough random surface surfaces, and parallel plate assumptions (i.e cubic law) do not hold. This influences interpreted aperture and resultant permeability at fracture and fracture network level. It is desirable to capture the influence of fracture geometry via distribution of expected behaviour.

Results

Single-phase permeability

- Increasing roughness causes significant decrease in the absolute permeability
- Decreasing correlation between surfaces causes decrease in permeability
- Permeability standard deviation increases with roughness and decreased correlation, the difference in permeability between different realisations becomes more pronounced

Two-phase permeability

- Low variance between different fracture realisations in the liquid or gas saturated regime
- High variance in the transition regimes for both liquid and gas saturations
- Gas remains immobile in large range of liquid saturations
- Non-linear shape of the permeability saturation curve
- Large number of disconnected liquid or gas components at low or high liquid saturations

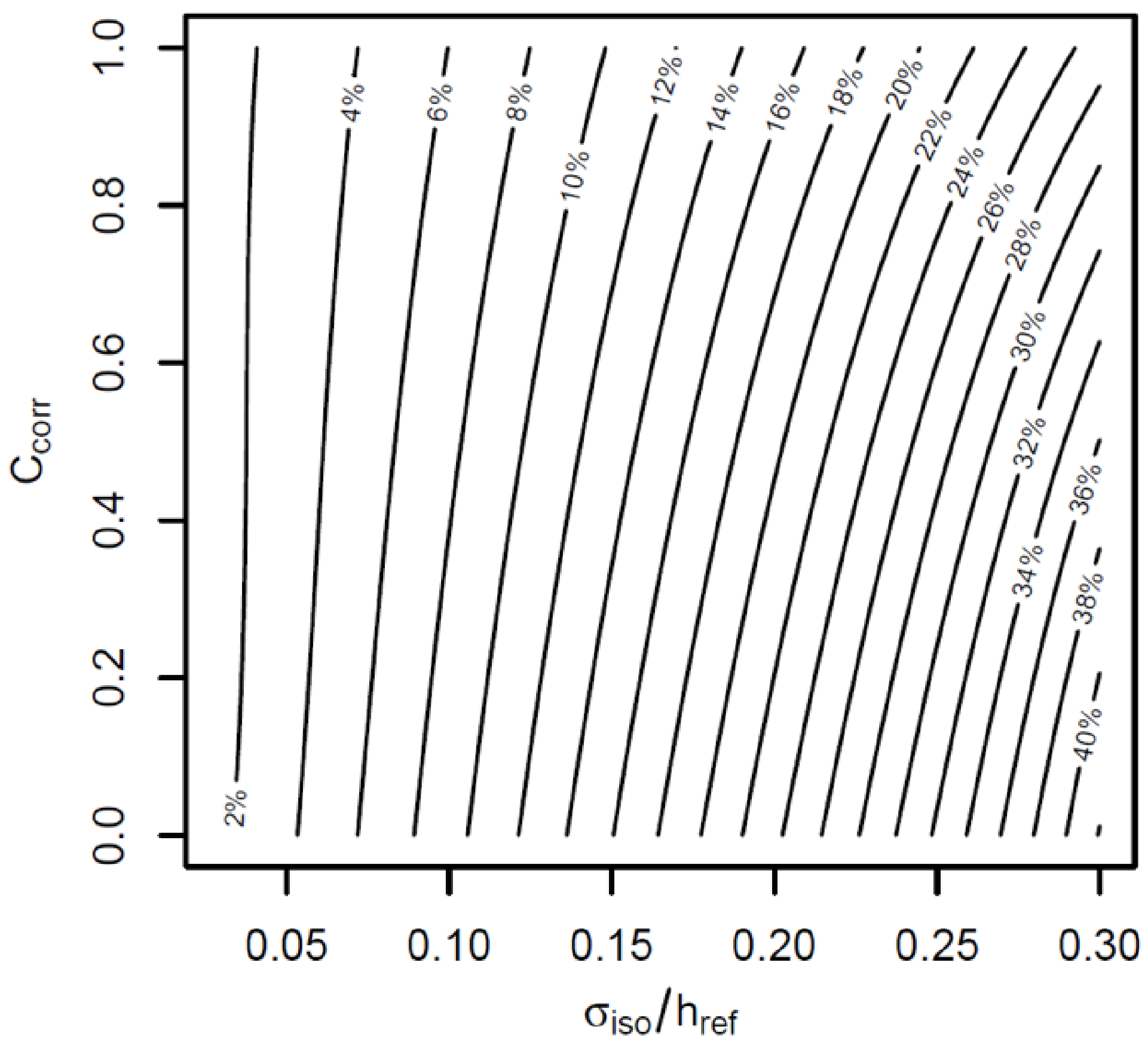

Figure 5: Single-phase results showing isolines of the mean reduction (nondimensionalised) of fracture permeability from a reference value.

Two-phase flow in rough fractures

The water and gas phases are initialised using a random distribution according to the prescribed saturation. A forcing term is applied driving the system to steady state and mimicking the pressure gradient. Having obtained the absolute permeability and expected flow rate from single-phase simulations, the relative permeability is calculated from steady-state average velocity values.

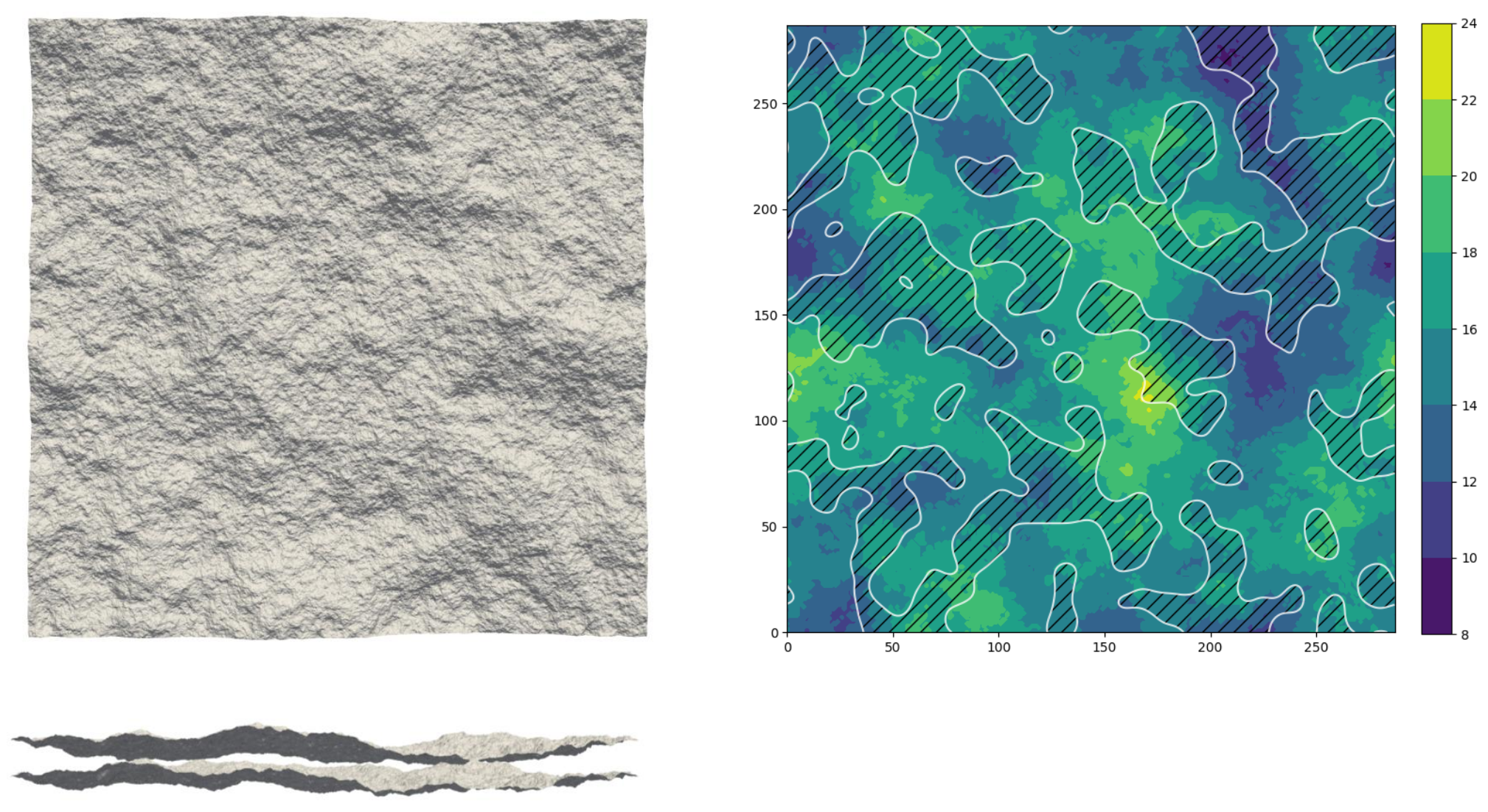

Figure 6: Aspects of two-phase flow modelling in fractures showing (left) a rough fracture geometry and (right) random initialisation of water and gas.

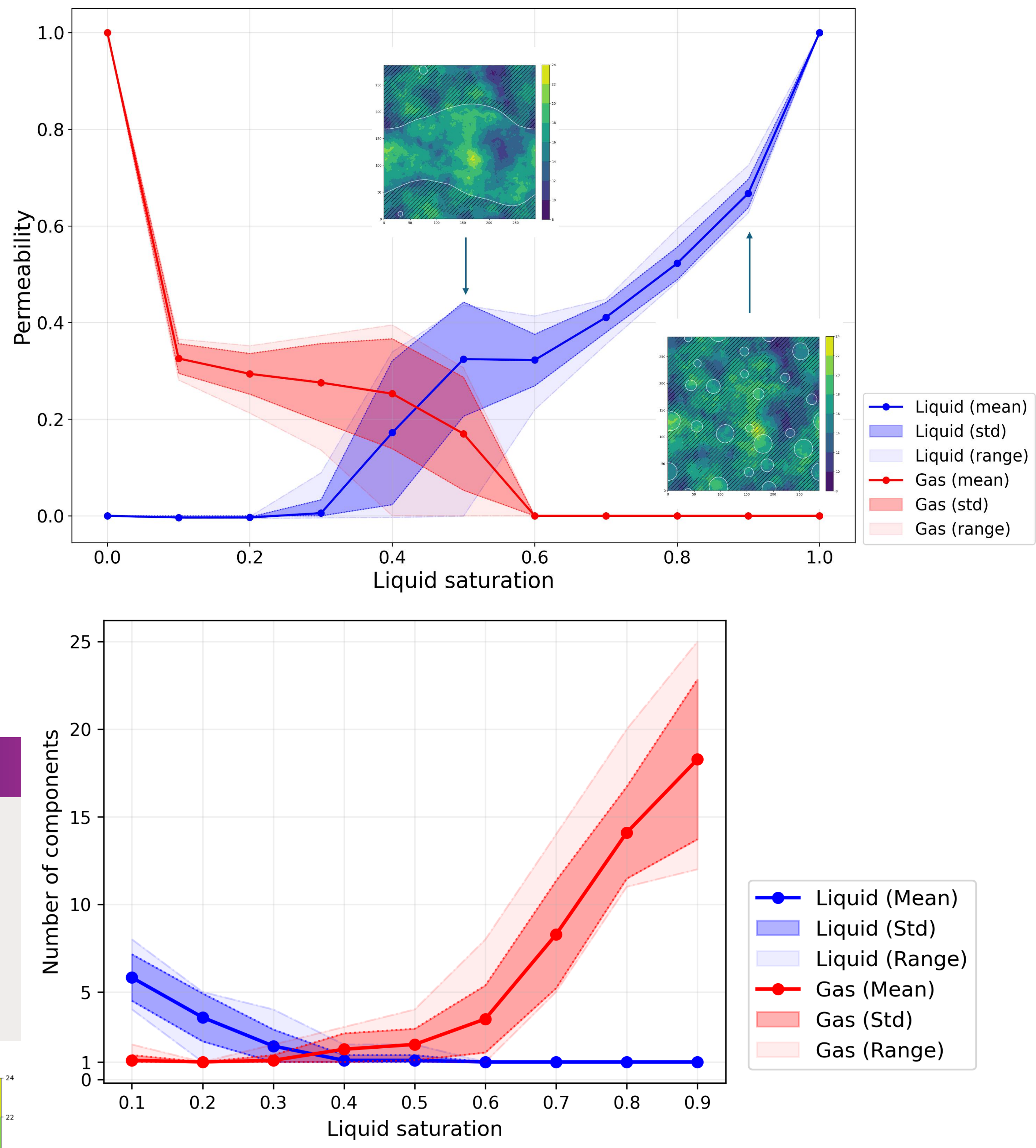

Figure 8: Graphs of (above) relative permeability and (below) number of liquid and gas in the steady state.

Conclusions and Future Work

Modelling has shown that (1) increased fracture roughness or decorrelation leads to increase in the standard deviation between results from different fracture realisations for both single- and two-phase flows, and (2) the permeability of liquid and gas are non-linearly dependent on saturation. Future work will apply this methodology to pressure driven flows to facilitate the generation of relative permeability curves and integration into DFN modelling.

✉ d.sashko@uq.edu.au
in Dmytro Sashko
@researcher
uq.edu.au

School of Mechanical and Mining Engineering

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