Bridging Computational Mechanics and Machine Learning in Geomechanics: *Insights for Subsurface Engineering*

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Abstract

This seminar presents a journey through innovative research at the intersection of computational geomechanics, machine learning, and subsurface engineering. By coupling advanced numerical methods with data-driven techniques, it aims to reveal innovative solutions to persistent challenges in understanding and predicting complex geomechanical behaviour. The talk will span three interconnected research topics:

1. Model Reduction for Borehole Stability - Solids Production in Weak Carbonate Reservoirs: The first part of the presentation focuses on the development of a computational framework for predicting solids production in carbonate reservoirs. The work, initiated in collaboration with PETRONAS, combines extensive rock characterisation experiments and finite-discrete element method (FDEM) simulations to assess mechanical failure at the wellbore wall under varying stress and fluid flow conditions. The framework not only reproduces experimental outcomes but also facilitates field-scale predictions through a user-friendly software tool. The predictive capabilities allow users to estimate solids production based on reservoir-specific input parameters, bridging the gap between laboratory tests and operational field applications.

2. Digital Twin of Westerly Granite Rock Samples - Machine Learning Applications in Fluid Flow Through Rocks: The second part addresses the dynamic permeability behaviour of faulted rock samples under stress. By integrating triaxial test data with machine learning-enhanced numerical simulations, the study reveals permeability variations within fault zones at different deformation stages. The inverse modelling approach highlights key findings, such as permeability increases of up to 400 times the baseline at critical slip stages and significant heterogeneity along the shear zones due to damage zone connectivity. These insights enhance our understanding of fluid flow in fractured rocks and have implications for applications such as hydrogen storage, geothermal energy, and CO_2 sequestration.

3. FEM-Based Learning - Embedding Neural Networks into PDEs as Trainable Operators for Scientific Machine Learning: The final segment introduces a novel paradigm for embedding neural networks within partial differential equation (PDE) systems as trainable operators. Traditional PDE models rely on known physical laws but struggle with phenomena governed by incomplete or unknown formulations. By embedding machine learning models directly into the PDEs, this approach retains the interpretability of physics-based models while capturing data-driven patterns. PyTorch-based neural networks are integrated within finite element solvers, enabling the training of operators using PDE solutions without requiring explicit input-output datasets. This methodology facilitates model reduction, enhances surrogate

modelling, and enables the discovery of emergent physical behaviours in large-scale systems.

Together, these studies highlight a targeted approach to understanding key geomechanical phenomena. By bridging physics-based modelling with experimental data and machine learning frameworks, this work provides insights and robust methodologies for subsurface exploration, resource management, and enhanced risk assessment in geomechanical engineering.

About the author

Dr Ado Farsi is a Visiting Researcher in computational mechanics at Imperial College London and University College London (UCL), Founder and Co-director of Tanuki Technologies Ltd and a Lead Scientific and Engineering Consultant at Imperial College Consultants (ICON). Dr Farsi has been an invited speaker and session organiser at several international conferences (WCCM, ECCOMAS, USNCCM). He is considered a world expert in computational mechanics, including finite element (FEM) and discrete element (DEM) modelling and machine learning (ML). His expertise extends to solid and fluid mechanics, with a particular focus on rock, concrete, and ceramic materials. Dr Farsi's research spans from rock mechanics, the study of fibre-reinforced concrete tunnels to the optimisation of catalyst supports for the production of hydrogen. He has more than ten years of experience in collaborating with industries and government bodies from different engineering sectors such as Petronas, Johnson Matthey and Transport for London. He has been training industry research scientists, supervising Master's students and teaching undergraduate and postgraduate students at Imperial College London and University College London. Dr Farsi has been a member of the Royal Society's RAMP committee (Rapid Assistance in Modelling the COVID Pandemic) that provides the UK government with scientific advice during the COVID-19 pandemic. He was also the representative of postdocs and fellows of the Earth Science and Engineering Department at Imperial College London and he is currently a committee member of the Imperial Postdoc and Fellows Enterprise Network.