14th Annual Meeting
Abu Dhabi, United Arab Emirates and Online
30 May – 2 June 2022 | Hybrid Event
Abstract ID: 457
An Uncertainty Quantification Workflow for Naturally Fractured Reservoirs using Proxy Modelling based on Poro-mechanically Informed Flow Diagnostics Simulations

Lesly Gutierrez Sosa, Heriot-Watt University
Sebastian Geiger, Heriot-Watt University
Florian Doster, Heriot-Watt University
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• Implementation
• Application – Case Study : Carbonate Reservoir Model
• Conclusions
Introduction

Reservoir Performance Prediction is a challenge

- Change in Flow Paths
  - Reservoir connectivity
- Change in Dynamics
  - Productivity and injectivity
- Challenge
  - Screening poro-mechanics
  - Reducing CPU cost
- Simpler Practical Approach
  - Poro-mechanically-informed flow diagnostics

Complexity
Heterogeneity
Stress
Dependency
Uncertainty

Petrophysical properties changes

\( \sigma_{\text{eff}} \leftrightarrow p \)
Objective

- **Stochastic Realisations**
- **Hydro-mechanical Coupling**
  - Reservoir Model (Pressure Solver)
  - Geomechanical Model (Mechanics Solver)
  - \( p \), \( k(u) \)
- **Flow Diagnostics**
  - TOF
  - Swept Vols.
- **Model Screening**
  - Poro-mechanics
  - No poro-mechanics
- **Detailed Reservoir Studies**
  - Full-Physics Simulations
  - Coupled Simulations
  - Flow Simulations
Poro-mechanically Informed Flow Diagnostics (FD)

Production – Injection Operation (0.5 PV injected)

Permeability

Time of Flight ($\tau$)

Inter-well Flow Regions

w/o Poro-mechanics

w/ Poro-mechanics

Fracture Permeability along yy-component (mD)

$$\log_{10} [\tau^* (\text{sec})]$$

Uninvaded Pore Volume

INJ1-PROD1
Discretised macroscale constitute model

\[ \mathbf{T}(\mathbf{u}^{c,r}) \mathbf{p}^{c,r+1} = \mathbf{f}_p \quad \text{where} \quad \mathbf{k}_f(\mathbf{u}^{c,r}) \]

\[ \mathbf{K} \mathbf{u}^{c,r+1} = \mathbf{f}_u + \mathbf{Qp}^{c,r+1} \quad \text{then} \quad r = r + 1 \]

- **Pressure Solver**
- **Mechanics Solver**
- **Stress-Dep. Correlation**
- **Recompute Transmissibility**
- **Pressure Solver**
- **Flux Solver**
- **Flow Diagnostics**

Incompressible fluid pressure equation

\[ -\nabla \cdot \left[ \frac{\mathbf{k}_f(\mathbf{u})}{\mu} \nabla (p - g\rho_f z) \right] + q = 0 \]

Linear momentum balance equation

\[ G\nabla^2 \mathbf{u} + (G + \lambda)\nabla \nabla \cdot \mathbf{u} = -\alpha \nabla \mathbf{p} - \rho b \]

**Stress dependency**
- \( \mathbf{k}_m(\mathbf{u}), \phi_m(\mathbf{u}) \)
- \( \mathbf{k}_r(\mathbf{u}), \mathbf{P}_c(\mathbf{u}) \)
- Matrix-Fracture
- transfer rate

(Gutierrez Sosa et al., 2020)
(Gutierrez Sosa et al., 2022)
**Application – Amellago Model**

Analogue of the Jurassic Arab Formation, Qatar

Subjected to production induced changes and gravity load
- Continuous and thin fractured carbonate bodies
- Heterogeneous petrophysical properties
- Heterogeneous matrix stiffness

(Agada et al., 2013)
Effect on Permeability and Productivity

- Subtle permeability reduction
- Substantial reduction of productivity
- Addition of unproductive layers

When accounting for poro-mechanics:

- Differences in reservoir connectivity, recovery and injectivity profiles, breakthrough time

Comparison of cases w/ Poro-mechanics:

- Computational efficiency: whole workflow took 20 min.
Proposed Uncertainty Quantification Workflow

Uncertainty parameters
- Boundary conditions, permeability model, stress regimes and some mechanical Moduli
- ANN-based proxy model
- 335 poro-mechanically informed FD – 3.5 days
Proxy-based Sensitivity Analysis

- Non-linear and interaction relationship between input parameters
- Identification of most influential parameter
- Guiding further experimental designs

Validated Proxy-Model of Swept Oil Volume

Simulated Swept Oil Vol. (x10^6 m^3)

ANN Neural Network
- R^2-Training = 0.987
- R^2-Validation = 0.975

Sobol (Global) Sensitivity Analysis

- Boundary Conditions
- Isostress Permeability Model
- Isostrain Permeability Model
- Matrix Young's Modulus
- Stress Regimes
- Fracture Young's Modulus
- Solid Stiffness Modulus

Monte Carlo realisations = 65,000

Total Effects in terms of Fractional Change of Proxy-Predicted Swept Oil Volume
Proxy-based Uncertainty Quantification

CDF and PDF functions of Swept Oil Volume

- P10, P50, Base P90
- Monte Carlo Realisations = 65,000
- Monte Carlo Realisations w/ Fracture-Dominated Flow = 40,068
- PDF of Proxy-Predicted Swept Oil Volume
- CDF of Proxy-Predicted Swept Oil Volume
- Base Case (w/o Poro-mechanics) Swept Oil Volume = 7.418 x 10^6 m^3
- P10 Swept Oil Volume_{Proxy-Prediction} = 6.39 x 10^6 m^3
- P50 Swept Oil Volume_{Proxy-Prediction} = 7.215 x 10^6 m^3
- P90 Swept Oil Volume_{Proxy-Prediction} = 7.945 x 10^6 m^3
- Broad exploration using 1000’s MC realisations
Clustering and Model Screening

- Identification of candidates to be studied in more detailed
- Candidates that cover the full range of uncertainty

Cluster Analysis

Selected cases (simulated)
Conclusions

Integration of Poromechanics in Flow Diagnostics Framework
- Feasible and computationally efficient
- Quick screening of poromechanical effects
- Complement to reservoir simulations workflows

Application of Poromechanical informed Flow Diagnostics
- Amellago carbonate model
- Assess of petrophysical and mechanical heterogeneity

Involvement in an Uncertainty Quantification Workflow
- Decision-making workflows
Thank you / Questions

Lesly Gutierrez Sosa, PhD Student, Heriot-Watt University
Prof. Sebastian Geiger, Heriot-Watt University
Prof. Florian Doster, Heriot-Watt University

lmg1@hw.ac.uk  S.Geiger@hw.ac.uk  F.Doster@hw.ac.uk