Digital Rock Physics: Digital In-Situ Conditions

ARMA workshop
Digital Rock Physics
Derived Rock Mechanics Properties
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- M2M’s GeoDict Software
  - performs 3d image processing
  - predicts physical rock properties based on CT and SEM images
  - automates workflows and interfaces to MATLAB, EXCEL, Abaqus, Fluent....

- GeoDict Software development since 1998
- Spin off from Fraunhofer Society in September 2011
Basic Principle of DRP

Sampling → Imaging → Image Processing → Simulation
Advantages of DRP

- generates results faster and at lower costs
- requires lower quality of rock material (e.g. cuttings)
- is non-destructive: derives all parameters from one core
- enables sensitivity analysis of parameters via fast solvers
- fosters understanding of processes
### Math2Market
Digital Rock Physics Portfolio

**Geometrical parameters**
- Porosity
- Pore size distribution
- Percolation
- Surface area
- Tortuosity

**Flow parameters**
- Absolute permeability
- Multi-scale flow
- Multi-phase flow
- Relative permeability
- Cap. pressure curve

**Electrical Parameters**
- Formation factor
- Resistivity index
- Saturation exponent
- Cementation exponent

**Mechanical parameters**
- Elastic moduli
- Stiffness
- In-Situ conditions
Rocks in a reservoir are exposed to elevated pressures and temperatures (in-situ conditions).

Generally in-situ conditions are not maintained during DRP workflows.

Changes in the pressure and temperature conditions impact the properties of fluids: density, viscosity, solubility of phases in the fluid.

These changes lead to changes in the pore space.
Need for in-situ conditions in DRP

Uncompressed image

Compressed image (3%)
In-Situ DRP techniques

In-Situ imaging

In-Situ modelling
Detailed In-situ DRP workflow
In-situ simulation I

- Cropping
- Noise reduction
- Artifact reduction

Detailed In-situ DRP workflow
In-situ simulation II

Solids

Pore space

Segmentation

Detailed In-situ DRP Workflow
In-situ simulation III

Numerical compression

Absolute resistivity

Absolute permeability

Cap. pressure
Saturation

Resistivity Index

Relative permeability
Mechanical Properties

- Two mineral phases
  - Quartz \( (E = 94.5 \text{ GPa}, \nu = 0.074) \)
  - Void \( (E = 0 \text{ GPa}, \nu = 0) \)

- FeelMath solver
  - Lippmann-Schwinger formulation for linear / non-linear mechanics

- Elastic properties
  \( (E = 46.9 \text{ GPa}, \nu = 0.108) \)

- Uniaxial macroscopic stress
  - Periodic boundary conditions
  - Stages [GPa]: 0.12, 0.24, 0.48, 0.71, 0.95, 1.43 (up to 3% compression)
Lippmann-Schwinger equations for linear elasticity


Reference stiffness

\[ \epsilon(u) = E + \epsilon(v) \]

Strain fluctuation

\[ \tau = (\mathbb{C} - \mathbb{C}_0) : \epsilon(u) \]

Stress polarization

Solution by applying

\[ \epsilon(v) + \Gamma_0 \ast \tau = 0 \]
\[ \epsilon(u) + \Gamma_0 \ast \tau = E \]

the Green operator

Convolution integral

\[ (\Gamma_0 \ast \tau)(x) = \int_{\Omega} \Gamma_0(y) \tau(x - y) dy \]

Integral equation

\[ \epsilon(u) + \Gamma_0 \ast ((\mathbb{C} - \mathbb{C}_0) : \epsilon(u)) = E \]
\[ (I + B_\epsilon)\epsilon = E \]
Deformation of 3D Images

Step 1
- Solve Lippmann-Schwinger equation
- Integrate strain field to obtain displacement vector field on the un-deformed geometry

Step 2
- Move voxel according to displacement field
- Cut voxel with deformed mesh
Deformation of 3D Images

- **Step 3**
  - Determine optimal threshold
  - Perform segmentation of the grey value image
  - Result: “boxel” image

- **Step 4**
  - Resample the “boxel” image to obtain a voxel image (with the original resolution)
Porosity and Pore Size Distribution

- Porosity: 18.4 changes to 15.7%
- Most frequent pore throat diameter: 8.8 changes to 7.4 µm
- Granulometry and Porosimetry
Absolute and Relative Permeability

- Absolute permeability: 108 changes to 66 mD
- Relative permeability

- Two flow solver: LIR-Stokes and SIMPLE-FFT
Electrical Conductivity and Resistivity Index

- Electrical Conductivity (Brine 5 S/m): 0.17 S/m
- Formation resistivity factor: 27 changes to 39
- Explicit-Jump immersed interface method
Capillary Pressure

- Irreducible WP saturation: 18%
- Displacement pressure changes from 24 to 29 kPa

- Pore morphology method

Air drains Brine with saturation stages 75%, 50% and 25%
Flow and mechanics are expensive to compute
  - Relative permeability is most expensive

Efficient solver allow:
  - Property simulations overnight
  - Simulations on large data sets (>2000³)
  - Sensitivity analysis

**Solver Performance**

<table>
<thead>
<tr>
<th>Property</th>
<th>Flow</th>
<th>Flow</th>
<th>Resistivity</th>
<th>Two phase distribution</th>
<th>Mechanics</th>
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</thead>
<tbody>
<tr>
<td>Solver</td>
<td>SIMPLE-FFT</td>
<td>LIR Stokes</td>
<td>Explicit Jump</td>
<td>Pore Morphology</td>
<td>FeelMath</td>
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<td>Runtime [h]</td>
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<td>3.1</td>
<td>0.6</td>
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<td>9.4</td>
<td>5.0</td>
<td>97.1</td>
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</tbody>
</table>

Runtime and memory requirements per direction for a data set of 720x720x1024 voxels. Computer with 16 Cores and 128 GB RAM.
Outlook

**Evaluation** - comparison of structures generated by:
- In-situ CT measurements (Zeiss Xradia)
- Numerical compression of conventional CT scans

**Improvements** of the workflow e.g. to get realistic pressure:
- Triaxial compression
- Segmentation of all present phases
- Incorporation of special properties for grain-grain contacts in the simulation of deformation
- Incorporation of poroelasticity
Conclusions

- In-situ conditions for reservoir rocks are characterized by elevated pressure and temperature conditions.
- Influence of temperature can be considered by adjustment of the fluid and mineral phase input parameters.
- Pressure changes affect the 3D geometry of the rock and have to be corrected.
- Non-consideration of the in-situ pressure can lead to substantial errors in the derived DRP parameters.
- Simulation of the in-situ conditions represents an alternative for in-situ measurements.
Thank you for your attention!