Geomechanics for OPM Flow Simulation

Geomechanics Directly on Corner-Point and Polyhedral Grids

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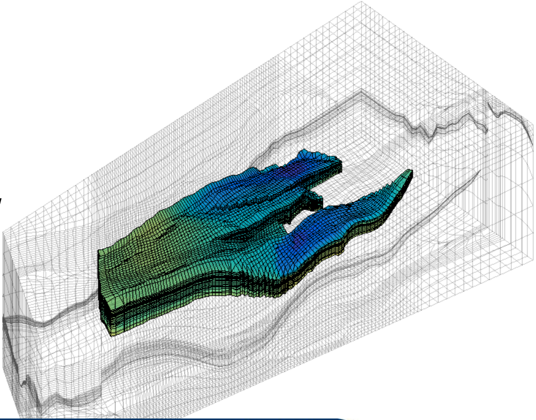
SINTEF Digital

Work in progess

Introduction

- Background
- Formulation
- Geomechanics in flow
- Discussion points for OPM FLOW

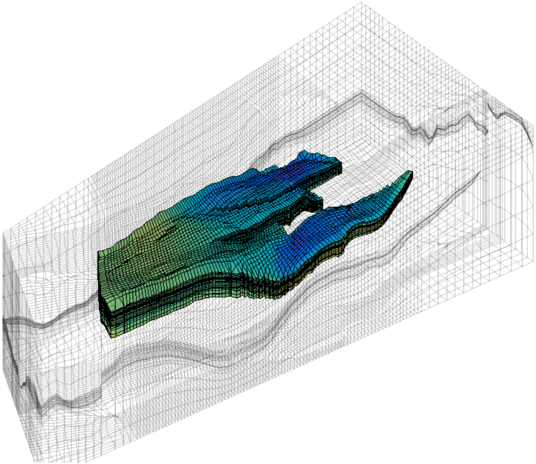


Background

Aim: Coupled

- multiphase flow simulation
- geomechanical simulations

on the **same** reservoir grid:

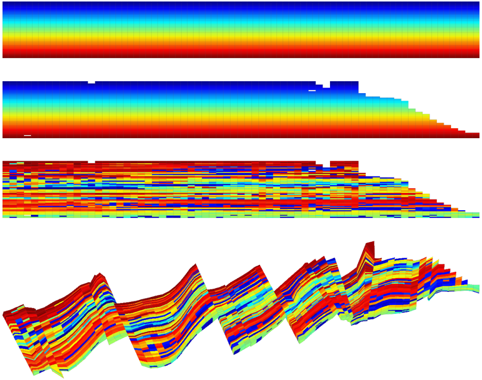


Numerical methods:

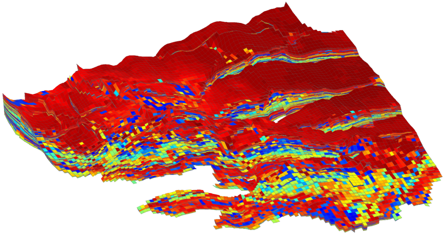
- Two Point Flux Approximation + Mobility Upwind (black-oil flow equations)
- Virtual Element Method (VEM) (geomechanical equations)

Stratigraphic models

- Reservoir models with irregular structures : fractures, layers, faults

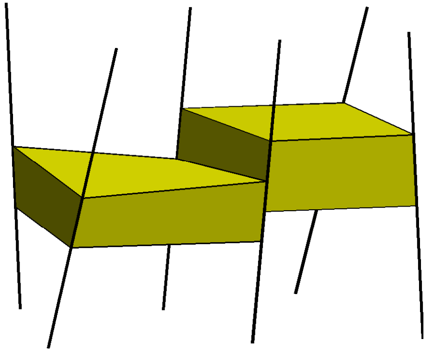


stratigraphic structure

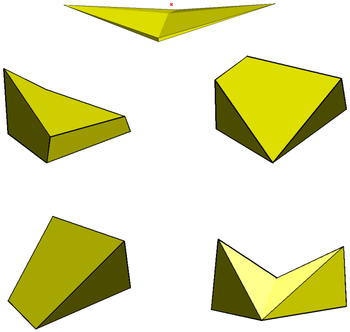


Gullfaks reservoir model

Cell shapes



Corner-point grid



Irregular cell shapes

Biot's equations of linear poroelasticity

Force equilibrium equation:

$$\nabla \cdot \boldsymbol{C}\varepsilon(\boldsymbol{u}) - \alpha \nabla p + \boldsymbol{f} = 0$$

Mass conservation equation:

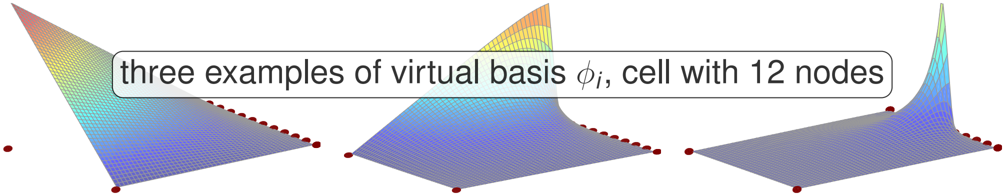
$$\frac{\partial}{\partial t}(\alpha \nabla \cdot \boldsymbol{u} + S_\epsilon p) - \nabla \cdot \frac{k}{\mu} \nabla p = q$$

α : Biot-Willis coefficient
$\boldsymbol{f}$: volumetric external force
S_ϵ : constrained specific storage
k : permeability
μ : fluid viscosity
q : fluid source term

- Unknowns are mechanical displacements $\boldsymbol{u}$ and fluid pressure p
- The coupling from mechanics to fluid occurs via the divergence term $\nabla \cdot \boldsymbol{u}$ (volume change).

Virtual Element Method (VEM)

- Virtual element method can handle **general polyhedral grids**.
- New theoretical framework for mimetic methods (long-standing effort: Brezzi, Lipnikov, Manzoni, Veiga, ...)
- The **VEM trick**: In a cell, let $\mathcal{P}$ denote the **projection** operator with respect to the bilinear form $a(\cdot, \cdot)$ into the approximation space (linear displacement). Then, the **projections** of the basis elements can be computed **exactly** from the degree of freedom (nodal displacement). The basis element themselves are not computed (hence, **virtual**)



three examples of virtual basis ϕ_i, cell with 12 nodes

Virtual Element Method (VEM)

- Linear elasticity

$$\nabla \cdot \boldsymbol{\sigma} + \boldsymbol{f} = \boldsymbol{0}, \quad \sigma = \boldsymbol{C}\varepsilon$$

- Linear elasticity **weak form**:

$$a(\boldsymbol{u}, \boldsymbol{v}) := \int_\Omega \varepsilon(\boldsymbol{v}) : \boldsymbol{C}\varepsilon(\boldsymbol{u})\, d\boldsymbol{x} = \int_\Omega \boldsymbol{v} \cdot \boldsymbol{f}\, d\boldsymbol{x}.$$

- Orthogonal **projection** $\mathcal{P}$ on the linear displacement space,

$$a^K(\boldsymbol{u}, \boldsymbol{u}) = a^K(\mathcal{P}\boldsymbol{u}, \mathcal{P}\boldsymbol{u}) + a^K((I - \mathcal{P})\boldsymbol{u}, (I - \mathcal{P})\boldsymbol{u}).$$

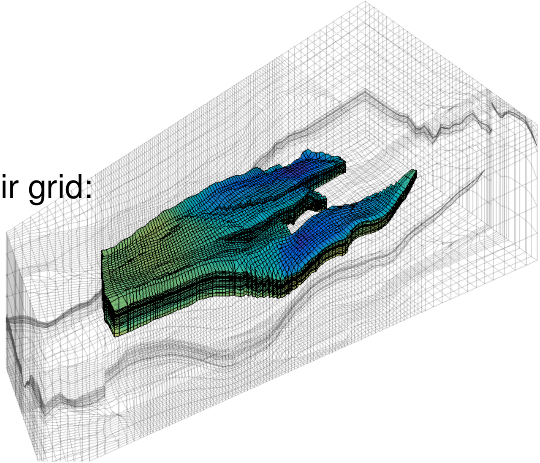
- VEM bilinear form $a_h^K(\cdot, \cdot)$:

$$a_h^K(\boldsymbol{u}, \boldsymbol{u}) = \underbrace{a^K(\mathcal{P}\boldsymbol{u}, \mathcal{P}\boldsymbol{u})}_{\text{exact}} + \underbrace{s^K((I - \mathcal{P})\boldsymbol{u}, (I - \mathcal{P})\boldsymbol{u})}_{\text{regularization term}}$$

Geomechanics in OPM
Geomechanics and flow with same data file

Aim: Simple workflow for
- flow simulation
- geomechanical simulations

using the **same** data file and reservoir grid:



Tools:
- OPM flow
- Virtual Element Method (VEM) (geomechanical equations)

New keywords: INPUT

- RUNSPEC section
  - MECH: turn on mechanical solves
- GRID section:
  - BCCON: set boundary condition regions (part of standard OPM Flow)
  - Isothermal:
    - YMODULE: Youngs module
    - PRATIO: Poisson ratio
    - BIOTCOEF: Biot-coefficient (not used but read/processed)
    - POELCOEF: poroelastic coefficient (relate to BIOTCOEF)
  - Thermal :
    - THELCOEF: thermoelastic coefficient (related to THERMEXP)
    - THERMEXP: thermal expantion coefficent (not used but read/processed)

New keywords: INPUT

- REGION section:
  - STRESSEQUILNUM: stress equilibrium regions
- SOLUTION section:
  - STRESSEQUIL: initial stress equilibrium
- SCHEDULE section
  - BCPROPS: defines boundary conditions (part of standard OPM Flow but extended for mechanical calculations)

New keywords: OUTPUT

- Stress: STRESSXX, STRESSYY, STRESSZZ, STRESSXY, STRESSXZ, STRESSYZ
- Strain: DELSTR and STRAIN similar notation as with stress
- Displacement: DISPX, DISPY, DISPZ
- Forces/potentials:
  - MECHPOTF: total potential
  - PRESPOTF: potential due to pressure changes
  - TEMPPOTF: potential due to temperature changes
- Input: all new keywords in the grid section

Code

Standard flow

- Input: `opm-common`
- Output: `opm-simulators`
- Grid processing: `opm-grid`
- Utilities for mechanics equations: `opm-upscaling` in the geomechanical part
- Utilities to facilitate geomechanical add-on (or others): `opm-models` and `opm-simulators`

Code: opm-flowgeomechanics

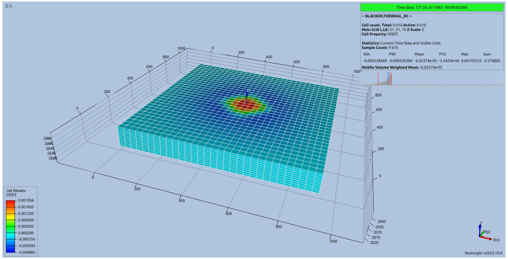
- New model: `EclGeomechModel`
  - has `elasicitysolver_` as member
- New problem: eclproblemgeomech
  - inherits from `EclProblem` (now FlowProblem)
  - has `EclGeomechModel` as member
- Implemented elasticitysolvers:
  - `VemElasisitySolver`
  - `ElasisitySolver` (opm-upscaling fem based)
- Extra output: `vtkgeomechmodule`
- New executables:
  - `flow_geomech+`: three-phase isothermal with mechanics
  - `flow_energy_geomech+`: three-phase thermal with mechanics

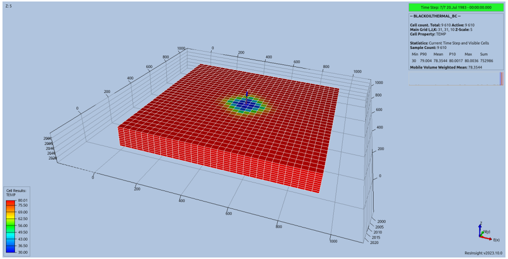
Code is currently at https://github.com/hnil/opm-flowgeomechanics/

OPM flow geomechanics: STATUS

- Features:
  - All features from OPM flow from same data file
  - Geomechanics which same data file
  - Visualization:
    - Standard visualization of cell basedquantites ResInsight
    - Paraview visulaliation including nodebased quantities
  - Coupling: currently only one way(/explicit)
- Current limitations
  - Limitations of edge-conformal grids:
    - full processing missing (in progress)
    - CpGrid not edge conformal implementation (need wrapper)
  - Minimal parallels solvers support (In progress)
  - No automatic padding to extend flow models
  - probably more...

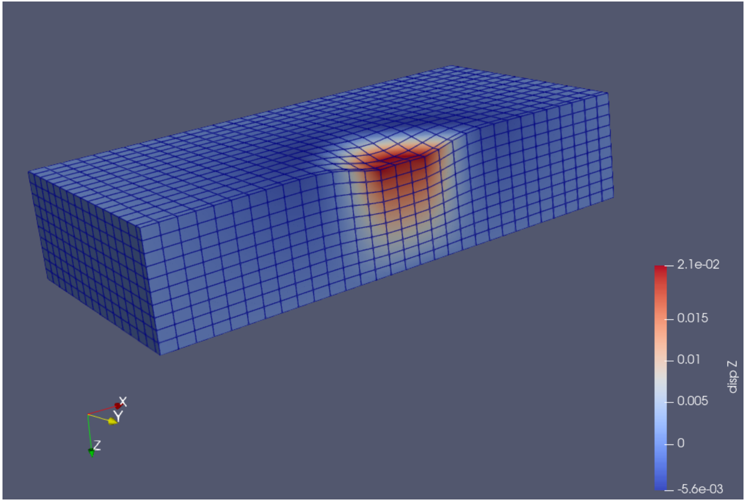
OPM Flow: simple example ResInsight





Displacement in the z direction and the thermal profile. Visualization is using ResInsight.

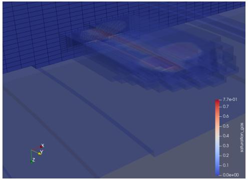
OPM Flow: simple example paraview



Displacement in the z direction paraview.

Related: Ongoing work

- Fracture flow:
  - Include flow from well through fracture into formation
- Thermal and hydraulic fracturing
  - Dynamic fracturing using Displacement Discontinuity Method (DDM) which is a variant of Boundary Element Method (BEM).
- Refinement: Example:
  Flow with
  dune-fem + AluGrid



Discussion points for OPM

- Grid requirements:
  - Edge conformal CpGrid
  - Element type of CpGrid
  - Parallel partitioning: Overlapping elements for node based discretization
  - Make PolyhedralGrid parallel?
- Grid nice to have:
  - Refinement in CpGrid (use code from Alugrid?)
  - Intersection between surface grids and 3D grid ?

Discussion points for OPM

- Coupling of models in opm:
  - Add on models: wells, aquifers, tracers
  - Thermal: included in system
  - Mechanics: add-on?, coupled system?
  - Coupled model: dumux?, new system?
- Finite element utilities: dune-fem, dune-pdelag, dune-vem
- Surface grids: dune-foamgrid ++ ? (dune-mmesh?, dune-corvedgrid)
- BEM utilities: general + multipole-expansion
  - bempp: old version used dune-grid (but is not mostly python)
  - betl: use dune-grid but is closed source
  - ??

Acknowledgement

- Founding:
  - Background (MRST): SEP founding from SINTEF
  - Investigation of methods: founding from Equinor
  - Implementation in OPM flow: founding from Equinor