On estimating geomechanical parameters from surface deformation with a particle method

Data assimilation for subsidence monitoring

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Publication date
2017

Document Version
Final published version

Citation (APA)

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.
On estimating geomechanical parameters from surface deformation with a particle method

Data assimilation for subsidence monitoring

Femke C. Vossepoel, Karlijn Beers, Ramon F. Hanssen, Denis Voskov
Agenda

• Introduction to subsidence
• Modeling subsidence: flow and geomechanics
• Assimilation to reconstruct subsurface processes
• Ongoing work and preliminary results
• Conclusions and Outlook
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• Introduction to subsidence
• Modeling subsidence: flow and geomechanics
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Examples of subsidence

1. Louisiana wetlands: fault activation (USGS)

2. Venice: mixed effect of groundwater and gas extraction

3. Groningen: seismic effects (NAM)
Subsidence, cause and effect

- Subsidence to first order related to pressure drop in reservoir (e.g. Geertsma, 1963)
- Relation with induced and natural seismicity poorly understood, for example in Groningen, San Jacinto, Basel.
Subsurface and surface monitoring

- Geodetic: satellites (InSAR, GPS) as well as in situ techniques (levelling)
- Production data from wells (bottom hole pressure, rates)
- Time-lapse seismic

Production rates and pressure

<table>
<thead>
<tr>
<th>Time-lapse seismic</th>
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<tbody>
<tr>
<td>10 000 m</td>
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Geodetic surface data

Valhall: Changes in volumetric strain 1992-2002 (left) and time shift from seismic data (right) Barkved et al (2005)
Integrated approach, focusing on three aspects:

- Data: sparse subsurface, high resolution surface data
- Model: coupled reservoir/geomechanics
- Data assimilation method: non-linear physics
Agenda

• Introduction to subsidence
• **Modeling subsidence: flow and geomechanics**
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Coupled flow-geomechanics

FLOW
Conversation of mass and Darcy’s law, estimating pressure, saturation, flow, (possibly including energy and thermodynamic phase equilibrium)

MECHANICS
Hooke’s law, estimating strain and relating porosity to pressure, strain, plastic strain, (possibly including thermal deformation)
Subsidence is typically modelled with a compaction model of a disk-shaped reservoir, using Geertsma’s analytical solution (1963), in combination with a time-dependent pressure distribution from a multi-layer reservoir model.

Reservoir models can have various levels of complexity. Including known and less well known geological features.

Groningen reservoir model
Mmax workshop March 2016, http://feitenencijfers.namplatform.nl

Bau (2014), after Geertsma (1963)
Reservoir compaction as uniaxial consolidation process: axial load is initially borne by fluid, and then shifted to skeletal frame (Terzaghi)

Compaction is not only affected by pore pressure, but also by boundary conditions, and total stress change: uniaxial assumption not always valid and often full coupling of flow and geomechanics required

Terzaghi’s uniaxially constrained soil consolidation, Craig 1997

Coupled simulation of compacting disk Lewis & Pao, 2003
Parameter uncertainty

- Fluid flow:
  - Permeability
  - Porosity
  - Saturation
  - Pressure

- Geomechanics:
  - Young’s modulus
  - Poisson’s ratio

- Geometry and geology
  - Overburden and reservoir layering
  - Faults and structure
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Bayes’ rule:

\[ f(\psi | \mathbf{d}) = \frac{f(\mathbf{d} | \psi)f(\psi)}{f(\mathbf{d})} \]

Assume state evolution can be described by Markov process:

\[ d\psi = g(\psi)dt + d\beta, \]

Minimum variance estimate:

\[ \hat{\psi} = \int \psi f(\psi | \mathbf{d})d\psi \]

To find this solution, several methods are being used for subsurface flow problems:

1. Randomized Maximum Likelihood (Oliver et al, 1996)
2. Ensemble Smoother (Van Leeuwen and Evensen, 1996)
3. Ensemble Kalman Filter (Evensen, 1994)
4. Ensemble Kalman Smoother (Evensen and Van Leeuwen, 2000)
5. Ensemble Square Root Filter (e.g., Zhang et al, 2010)
6. ES-MDA (Emerick and Reynolds, 2012)
7. Particle Filters (review: Van Leeuwen, 2009)
8. Markov-Chain Monte Carlo (e.g., Oliver et al, 1996)
Particle methods

- Approximate model uncertainty with ensemble of model realisations
- Weight each particle with difference observation-model
- Can be used as a smoother or as a filter

Bayes' theory:

\[ p_m(\psi | \mathbf{d}) = \frac{p_d(\mathbf{d} | \psi)p_m(\psi)}{p_d(\mathbf{d})} \]

\[ p_d(\mathbf{d}) = \int p_d(\mathbf{d} | \psi)p_m(\psi)d\psi \]

Represent model probability density by ensemble:

\[ p_m(\psi) = \frac{1}{N} \sum_{i=1}^{N} \delta(\psi - \psi_i) \]

Minimum variance estimator:

\[ \hat{\psi} = \int \psi p_m(\psi | \mathbf{d})d\psi = \frac{\int \psi p_d(\mathbf{d} | \psi)p_m(\psi)d\psi}{\int p_d(\mathbf{d} | \psi)p_m(\psi)d\psi} = \frac{\sum_{i=1}^{N} \psi_i p_d(\mathbf{d} | \psi_i)}{\sum_{i=1}^{N} p_d(\mathbf{d} | \psi_i)} \]
Particle filter – avoid ensemble collapse

- Resample to avoid ensemble degeneracy: sequential importance resampling

- Optimize the ensemble going forward by proposal density or kernel dressing (regularised particle filter)
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Particle Filter for Groningen Subsidence (1)

- Modeling subsidence with so-called Mogi sources, spherical sources of strain.
- Tested particle filter methodology on cases with increasing number of Mogi sources.
- Importance resampling (SIR) to prevent ensemble degeneracy.

![Diagram of Mogi source](image)

Mogi source, after Dzurisin, 2007

![Particle weights](image)

Particle weights

Testing with one, two and four Mogi sources

- **Modeling subsidence with so-called Mogi sources, spherical sources of strain.**
- **Tested particle filter methodology on cases with increasing number of Mogi sources.**
- **Importance resampling (SIR) to prevent ensemble degeneracy.**

with Karlijn Beers, Ramon Hanssen
Testing on subset of data with 19 Mogi sources and real InSAR data

- Ensemble size $N=1000$
- Signal $\sim 8$ mm, error $\sim 4$ mm
- RMSE assimilation result $\sim 6$ mm
- Representativeness Mogi source for subsidence?

InSAR data of 2009-2010 subsidence (mm)

residuals (mm)

analysis (mm)

with Karlijn Beers, Ramon Hanssen
Coupled reservoir-geomechanical model: AD-GPRS (Denis Voskov, TUD, Yifan Zhou, Timur Garipov, Stanford)

- Simplified geometry with full coupling, fully implicit methods makes model computationally efficient
Coupled flow-geomechanical – Experimental setup

- For testing: simplified, Terzaghi-like problem, 1D, 100 ensemble members
- Sensitivity studies to rock properties
- Relationship Poisson ratio-strain non-linear
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Conclusions and ongoing work

- Preliminary conclusions
  - Particle methods can be used to estimate geomechanical and flow parameters in non-linear simulations
  - Assimilation of real data require knowledge of model uncertainty/representativeness

- Outlook
  - Sampling strategies: hybrid methods?
  - Dynamic versus static forcing
  - Deep versus shallow causes of subsidence
Q&A
Outlook

- Uplift due to steam injection
- Other geological settings, offshore subsidence
- Surface effects of mining, geothermal energy
- Susidence related to water extraction (Ravenna, Italy, or Thailand)
- Sea level rise and coastal subsidence (Indus and Nile delta, Wadden Sea)
- Groundwater studies and shallow subsurface

Wadden Sea, Netherlands

Bangkok, Thailand
Groningen gas field as case study to address the following effects on subsidence through data-consistent parameterisation:

- Compartimentalisation
- Groundwater fluctuations and aquifer depletion
- Creep in caprock and overburden
- Induced seismicity
- Heterogeneities

From DINO, 2008, De Mulder, 2003, see also Ketelaar 2009

Bourne et al (2014)