Towards coupled flow-geomechanical data assimilation

Femke Vossepoel

with contributions of Antonis Mavritsakis, Irene Platteeuw, Karlijn Beers, Denis Voskov, Phil Vardon, Ramon Hanssen
Agenda

• Introduction to subsidence: cause and effect
• 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: cause and effect**
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Subsidence: cause and effect

Examples of subsidence

1. Louisiana wetlands: fault activation (USGS)

2. Venice: mixed effect of groundwater and gas extraction

3. Groningen: seismic effects (NAM)
Subsidence, induced seismicity

- 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.

Figure 4. Compaction in the Groningen reservoir at January 2012 calculated with the RTiCM model (from TNO, 2014). The difference between calculated and modeled subsidence is indicated at the benchmark locations (label: Subsidence diff). A red color indicates that the measured subsidence is larger than the modeled subsidence.

Due to the creep part of the RTiCM model, this model will lead to larger subsidence values at the end of field life (expected in 2080).

3.4 Discussion

The compaction models (RTiCM and Time Decay) both fit the delay character of the observed subsidence in the first 10 years after the start of the gas production (Fig. 3). They underpredict the maximum subsidence in the center of the subsidence bowl by 2–3 cm for the RTiCM model and 5–6 cm for the Time Decay model at the end of 2011. Spatially both compaction models show the same pattern of overestimation and underestimation (Fig. 4). An overestimation of the subsidence occurs in the eastern part and in the northwestern part of the field. An underestimation exists in the southwestern part of the field. The differences between the compaction models are in the amplitude of maximum compaction (RTiCM larger than Time Decay) and the shape of the subsidence bowl at the edges of the field. The RTiCM model predicts a slightly steeper subsidence bowl than the Time Decay model.

As is clear from Fig. 4, relatively large misfits (up to 8 cm) occur over the field. In the van Opstal (1974) method a depth of a rigid basement is assumed, which governs the shape of...
Subsidence can be observed with satellites (InSAR, GPS) as well as in situ techniques (levelling).

Fact sheet USGS

http://comet.earth.ox.ac.uk/for_schools_radar4.html

Subsurface monitoring

- Surface data on subsidence can be complemented by subsurface data from wells (bottom hole pressure, rates) as well as seismic

4D Seismic

Valhall: Changes in volumetric strain 1992-2002 (left) and time shift from seismic data (right) Barkved et al (2005)

Production rates and pressure

Artist impression Valhall field, including wells
http://offshoreenergytoday.com
Integrated approach, focusing on three aspects:

- Data: sparse subsurface, high resolution surface data
- Model: coupled reservoir/geomechanics
- Data assimilation method: non-linear physics
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Subsidence is typically modelled based on 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
Geomechanical modelling of compaction (1)

- Geertsma’s subsidence model: uniaxial compaction with effective stress resulting from pressure difference

\[ \sigma_x = \sigma_y = \sigma_r : \text{radial/lateral stress} \]

\[ \epsilon = \epsilon_y = \epsilon_r = 0 : \text{radial/lateral strain (laterally confined)} \]

\[ -\Delta p = \Delta \sigma' = \Delta \sigma_z' + 2 \Delta \sigma_r' \]

\[ \epsilon_z = \frac{(1 - 2\nu)(1 + \nu)}{E(1 - \nu)} \Delta \sigma_z' \]

Or

\[ \epsilon_z = C_m \Delta \sigma_z' \]

With \( \Delta \sigma_z' = \Delta p \)
Geomechanical modelling of compaction (2)

- Geertsma’s model provides a good first-order approximation of compaction and associated subsidence when assuming elastic behavior of the subsurface.
- How does subsidence develop over time?

\[
\begin{align*}
    u_z (r, 0) &= -2c_m (1 - v) \Delta p H R \int_0^\infty e^{-\varrho_0 J_1 (\alpha R) J_0 (\alpha r)} d\alpha \\
    u_r (r, 0) &= +2c_m (1 - v) \Delta p H R \int_0^\infty e^{-\varrho_0 J_1 (\alpha R) J_1 (\alpha r)} d\alpha
\end{align*}
\]
Reservoir compaction can be considered as a 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: coupling of flow and geomechanics required.
Generic model of coupled flow-geomechanics

**Flow** model, with governing equations:

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

**Mechanical** model to determine rock deformation:

Hooke’s law, estimating strain and relating porosity to pressure, strain, plastic strain, (possibly including thermal deformation)
In reality, compaction occurs in different layers: ground water variability, ground water extraction, peat oxidation, ...

Response of overburden may not be fully elastic. In Groningen salt creep may delay the surface response.

Glennie, AAPG, 2013

Mossop, Waddenacademie, 2013
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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Objective: estimate pressure state and corresponding subsidence based on a combination of surface observations (deformation) and subsurface observations (bottom-hole pressure, rate, seismic)

Approach: find solution that minimizes difference between (coupled flow-geomechanical) model and observations.
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. Ensemble Smoother (Van Leeuwen and Evensen, 1996)
2. Ensemble Kalman Filter (Evensen, 1994)
3. Ensemble Kalman Smoother (Evensen and Van Leeuwen, 2000)
4. Ensemble Square Root Filter (e.g., Zhang et al, 2010)
5. Randomized Maximum Likelihood (Oliver et al, 1996)
6. Particle Filters (review: Van Leeuwen, 2009)
7. Markov-Chain Monte Carlo (e.g., Oliver et al, 1996)
The practical implementation of the commonly used Ensemble (Kalman) methods have the general shape of:

$$\psi^a (x, t^*) = \psi^f (x, t^*) + \sum_{m=1}^{M^*} b_m r(x, t^*)$$

Where the term $$\sum_{m=1}^{M^*} b_m r(x, t^*)$$ involves a multiplication of the M representers or influence functions (involving the error covariances) with coefficients that effectively weight a set of model realizations with their difference from the observations. In the most commonly used EnKF:

$$\psi^a (x, t^*) = \psi^f (x, t^*) + C_{\psi\psi} H^T \left( HC_{\psi\psi} H^T + C_{dd} \right)^{-1} (d - H\psi^f (x, t^*))$$

With covariances $$C_{\psi\psi}$$ and $$C_{dd}$$ representing uncertainty in model and data.
In geomechanical applications, the estimated variable $\psi^a$ is a function of a state $x$, starting from an initial condition $x_0$ and (geomechanical) parameters $\gamma$. Observations $d$ will relate to the state (subsidence, pressure, rate), while the model $\psi^f$ will largely depend on choices of $\gamma$.

$$
\psi^a(x, \gamma, t^*) = \psi^f(x, \gamma, t^*) + C_{\psi\psi}H^T \left( HC_{\psi\psi}H^T + C_{dd} \right)^{-1} (d - H\psi^f(x, t^*))
$$

Typically, the covariances $C_{\psi\psi}$ and $C_{dd}$ are based on Gaussian assumptions. For flow problems, this tends to give satisfactorily results. How about geomechanical problems?

- Strongly non-linear (consolidation, fault slip)
- Coupled models
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:

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

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

Represent model probability density by ensemble:

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

Minimum variance estimator:

\[ \hat{\psi} = \int \psi p_m(\psi | d) d\psi = \frac{\int \psi p_d(d | \psi)p_m(\psi) d\psi}{\int p_d(d | \psi)p_m(\psi) d\psi} = \frac{\sum_{i=1}^{N} \psi_i p_d(d | \psi_i)}{\sum_{i=1}^{N} p_d(d | \psi_i)} \]
Resample to avoid ensemble degeneracy: sequential importance resampling

Optimize the ensemble going forward by proposal density or kernel dressing (regularised particle filter)
Approach

- Strain source distribution
- Inversion of geodetic double difference data
- Regularized Particle Filter for Darcy flow and slope stability
- Comparison Monte-Carlo methods and Ensemble (Kalman) methods
- Sensitivity fault reactivation
  - Sensitivity overburden lithology

- Data interpretation
- Coupled modeling and sensitivity
- Data assimilation
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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

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

Ensemble size N=1000

residuals RMSE = 6.16 [mm]

InSAR data of 2009-2010 subsidence (mm)

with Karlijn Beers, Ramon Hanssen
Regularized Particle Filter for Darcy flow

- Estimating permeability in a 1D Darcy-flow problem using a particle filter
- Resampling using the regularized particle filter (RPF)
- RPF finds good fit with analytical solution

\[ p(\psi|d) \approx \sum_{i=1}^{N} w_i K_h(\psi - \psi_i) \]

K: Kernel, h: Kernel width

\[ K_h(\psi) = \frac{1}{h^n} K\left(\frac{\psi}{h}\right) \]

with Antonis Mavritsakis, Phil Vardon
Slope stability: MCMC vs Regularized Particle Filter

- Comparison of regularized particle filter with Markov-Chain Monte Carlo method
- MCMC gives a better fit with the data

Regularized Particle Filter

MCMC vs Regularized Particle Filter

Comparison of analysis to reference - shear strength

with Antonis Mavritsakis, Phil Vardon
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 -1D Case

- Simplified, Terzaghi-like problem, 1D, 100 ensemble members
- Sensitivity studies to rock properties
Fault slip

- 2D finite element model (Plaxis) simulating fault slip and associated deformation resulting from differential compaction
- Sensitivity study to fault conditions: angle, friction coefficient, Poisson’s ratio, rock properties

With Irene Platteeuw, Marc Hettema, Ronald Brinkgreve
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Conclusions and ongoing work

Conclusions

- Subsidence involves processes in shallow and deep subsurface
- Geomechanical and flow parameters can be estimated with data assimilation
- Non-linearities and coupled models ask for Monte-Carlo based methodologies

Ongoing work

- Hybrid Monte Carlo/EnKF assimilation methods
- Dynamic versus static forcing
- Heterogeneities in overburden: integration of seismic and non-seismic
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
Q&A