Optimizing of Operational Strategies in Producing Gas Fields Mitigating Induced Seismic Risk

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M4ShaleGas Measuring, Monitoring, Mitigating, Managing the Environmental Impact of Shale Gas

Abstract

Pore pressure changes caused by the production of gas from reservoir rocks result in reservoir compaction, stress changes on faults, potential fault reactivation and related seismic activity. This seismic activity is expected to be affected by the amount of pressure change, the spatial distribution of the pressure changes relative to the distribution of the faults and the rate at which the pressure changes occur. One of the options to mitigate seismicity in the field during ongoing depletion is to reduce production in areas of high seismicity rates and/or to maintain pressures by local injection. Therefore, seismic activity can potentially be reduced by optimizing the production strategy of a field.

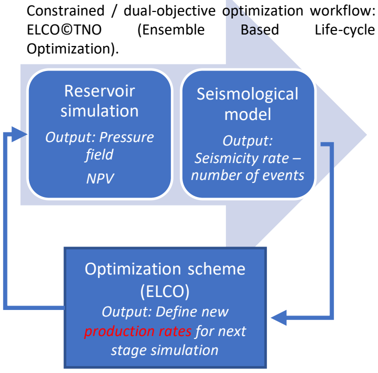
We have developed a workflow to find optimized production strategies that take into account the risk of induced seismicity. The two main ingredients of the workflow are: (1) the fast seismological forward model and (2) the optimization scheme. Two seismological approaches are presented: (1) **strain-based seismological model** and (2) **stress-based seismological model**. The optimization scheme is based on approximate gradients, and is flexible enough to allow for many operational parameters.

The performance of the workflow is demonstrated in a series of experiments representative of production scenarios in gas fields in the Netherlands. The results of these experiments demonstrate the potential for model-based reservoir management workflows to contribute to safe production of hydrocarbon resources.

Workflow

Objective: maximizing revenues (Net Present Value) while minimizing seismic risks (Seismicity rate – Number of events):

- Controlling variables: Production rates.
- Reservoir simulator: Eclipse.
- Seismological model: (i) **strain-based** and (ii) **stress-based** (MACRIS©TNO) approach.
- Constrained / dual-objective optimization workflow: ELCO©TNO (Ensemble Based Life-cycle Optimization).



The ELCO tool iteratively updates production rates (the operational strategy) using approximate sensitivities of gas production and number of events with respect to these rates such that production is maximized, or the number of events is minimized, or both.

Strain-based seismological model

We define a simple strain-based seismological model designed to satisfy two main goals:

- Linking the strain induced by reservoir compaction and the number of seismic events (e.g. Bourne and Oates, 2015)
- Including the dependence on strain and strain rate (i.e. cumulative compaction c and compaction rate c') of the rate of seismicity $\boldsymbol{\lambda}$.

$$\lambda = c'(t)g(c(t), c'(t))$$

implementation: allow for general form of g

start e.g., with: $g(c, c') = \alpha_0 + \alpha_1 c + \alpha_2 c'$
and: $c(x, y, t) = h(x, y)C\Delta p(t)$

Thus $\lambda(t) = \alpha_0 c'(t) + \alpha_1 c(t)c'(t) + \alpha_2 c'(t)c'(t)$
objective: minimize total number of events N:

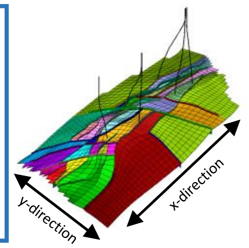
$$N = \iiint \lambda(x, y, t)\,dx\,dy\,dt$$

Remarks:

(1) For scenarios with same total production, when $\alpha_2 \neq 0$, the total number of events will be dependent on the production profile.

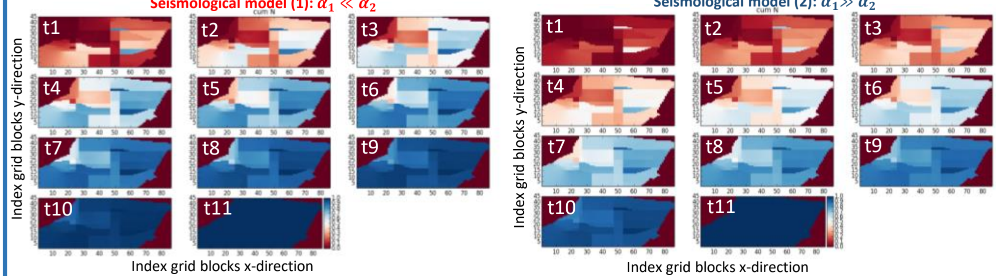
(2) The factor α_1 is used to increase the seismicity rate with increasing cumulative compaction (e.g., due to increased loading). For constant production/compaction the seismicity rate will increase in time.

(3) The factor α_2 is used to increase the seismicity rate with increasing compaction rate (e.g., due to reduced aseismic relaxation). Faster production is punished.



Forward models with fixed total production and different production rates

Normalized up-scaled cumulative number of events:



Increasing α_1 in Seismological model (2) leads to relatively less events at the onset of depletion.

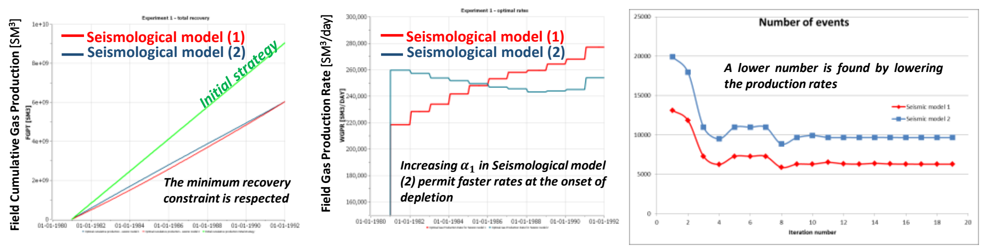
Results of the optimization – Example 1

Seismological model (1): $\alpha_1 \ll \alpha_2$

Seismological model (2): $\alpha_1 \gg \alpha_2$

***Initial strategy*: all wells produce at constant rate**

***Target*: minimize number of events with a minimum recovery constraint of 66%**



Results of the optimization – Example 2

***Initial strategy*: all wells produce at constant rate**

***Target*: maximum number of events allowed = 6500, with the maximum possible recovery**

Stress-based seismological model

We use an in-house developed fast stress-based seismological model (MACRIS©TNO):

- Each depleted reservoir grid block as a nucleus-of-strain contributes to the total stress change on the fault surface.
- For reservoir-rock contact along the fault, the pressure change is set equal to zero. For reservoir-reservoir contact along the fault, the pressure change is set equal to the one of the compartments (hanging wall or foot wall) with the largest pressure change.

From the full stress tensor on the fault, one calculates the coulomb stress change as:

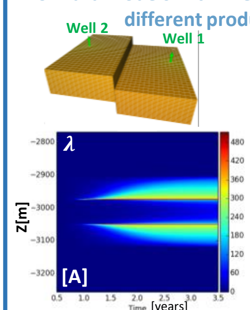
$$\tau = \tau_s + f(\sigma_n + P)$$

We follow the simplified version of Dieterich's model (Dieterich, 1994) proposed by Segall and Lu (2015) for the rate of seismicity:

$$\frac{\partial \lambda}{\partial t} = \frac{\lambda}{t_a}\left(\frac{\dot{\tau}}{\dot{\tau}_0} - \lambda\right)$$

where $\dot{\tau}$ is the coulomb stressing rate, $\dot{\tau}_0$ the background stressing rate. $t_a \equiv a\bar{\sigma}/\dot{\tau}_0$ is a characteristic decay time; with a a constitutive parameter quantifying the direct effect on slip rate in the rate-state friction law, and $\bar{\sigma}$ is the background effective normal stress. t_a is set to 50 years in our example and, and we assume a background stressing rate $\dot{\tau}_0$ corresponding to a stress drop of 1 MPa every 1000 years.

Forward models with fixed total production and different production rates



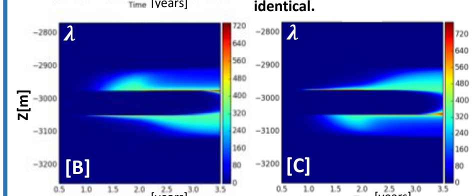
We present 3 scenarios:

[A] Well1 and well2 produce at constant rate Q during 4 years.

[B] Well 1 produces at 2*Q from 0 to 2 years and then well 2 produces at 2*Q from 2 to 4 years.

[C] Well 2 produces at 2*Q from 0 to 2 years and then well 1 produces at 2*Q from 2 to 4 years.

For the 3 scenarios the total field cumulative gas production at the end of the 4 years is identical.



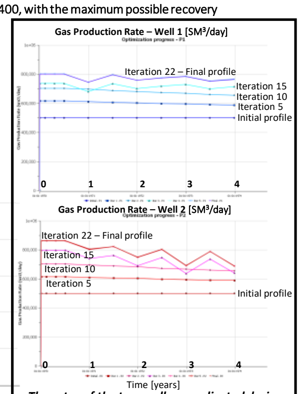
Different spatio-temporal seismity rate depending on the production rate strategy → seismological model suitable for optimization.

References
Bourne, S., & Oates, S. (2015). An activity rate model of induced seismicity within the Groningen Field (Part 1). NAM. Retrieved February 5, 2017, from http://feitenencijfers.namplatform.nl/download/rapport/8b6f2ff1-b98e-4148-a1db-bf06881579e5?open=false.
Dieterich, J. H., and B. Kilgore (1996), Implications of fault constitutive properties for earthquake prediction, Proc. Natl. Acad. Sci., 93(9),3787–3794.
Segall, P., and S. Lu (2015), Injection-induced seismicity: Poroelastic and earthquake nucleation effects, J. Geophys. Res. Solid Earth, 120, 5082–5103, doi:10.1002/2015JB012060.

Results of the optimization

***Initial strategy*: the two wells produce at the same constant rate**

***Target*: maximum seismicity rate λ allowed = 400, with the maximum possible recovery**



The rates of the two wells are adjusted during the optimization
The final rate-profiles are different for the two wells

Conclusion

It has been demonstrated that an optimization framework can be used to find optimal strategies to operate reservoirs in the presence of conflicting objectives.

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