KNGMG/PGK/SPE/KIVI Symposium
"The Science behind the Groningen Gas Field"
TU Delft, 1 February 2018

Induced Seismicity in the Groningen Field – Further Studies

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Background

- Jansen, J.D. and Herber, R.M., 2017: Research into induced seismicity in the Groningen field – further studies. *Netherlands Journal of Geosciences* **96** (5) s279–s284. https://doi.org/10.1017/njg.2017.21 (Only **subsurface** aspects!)
- Based on info from: open literature publications, discussions with many (Dutch and international) colleagues, participation in the Scientific Advisory Committee (SAC) for the 2016 NAM Winningplan, and membership of the Mijnraad
- My own expertise is in control of subsurface flow and mechanics, (i.e. only a subset of the topics discussed)
- I worked for Shell from 1986 - May 2010, and have worked for TU Delft from 1999 - now (full-time as of April 2010)
- I have currently no NAM or Shell-sponsored projects
- This presentation reflects my personal opinions

Further studies (NJG Special Issue paper)

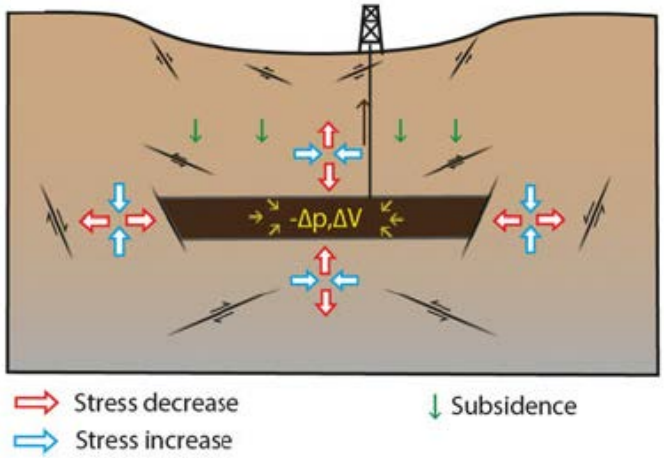
Research topic	Research type		
	Lab	Field	Theory
Understanding the source			
Monitoring of seismic events		X	
Pinpointing the location of seismic events		X	X
Determining *in situ* stresses below the reservoir		X	X
Understanding friction behaviour of reservoir and non-reservoir rock in faults	X		X
Understanding (time-dependent) deformation mechanisms of reservoir rock	X	X	X
Understanding (time-dependent) mechanical properties of salt and anhydrite	X	X	X
Understanding the direct and indirect effects of pore pressure changes on fault stresses	X		
Quantifying the effects of pressure propagation through faults outside the reservoir			
Assessing the hazard related to cyclic (seasonal) production and sudden rate changes			
Understanding the (dynamic) areal propagation of stress release along fault planes			
Quantifying the effect of multiple-event and aftershock generation by wave propagation			
Quantifying propagation to surface			
Gathering further earthquake statistics			
Gathering further data on near-surface soil conditions		X	
Testing the transient and long-term time-dependent h		X	
Numerically modelling wave propagation to			X
Data-driven prediction of wave pr		X	X
Assessing soil properti	X	X	X
Further dev			X
Red			
mbological theory to transient seismicity			X
mechanistic simulation			X
quantification with competing models			X
risk assessment methodology that can accommodate multiple models			X
anging the reservoir			
Understanding control mechanisms	X		X
Developing statistical methods			X
Developing methods for pressure control	X		X
Developing protocols			X

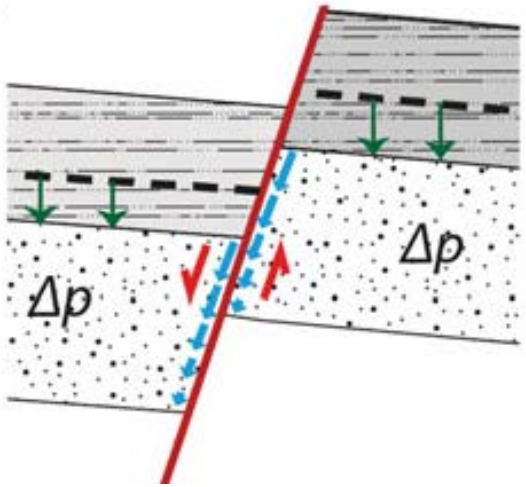
Not all covered in this talk

Source: Jansen, J.D. and Herber, R.M., 2017: Research into induced seismicity in the Groningen field – further studies. Netherlands Journal of Geosciences 96 (5) s279–s284. https://doi.org/10.1017/njg.2017.21

What do we (think we) know?

- Seismic energy originates from potential energy in overburden, not from plate tectonics => earthquakes are human-induced; not natural
- Earthquakes orginate from faults in or somewhat above/below the reservoir
- Offset faults are most likely sources
- Triggering: combination of
  - reduction in normal stresses
  - increase in shear stresses
  - reduction in pore pressure

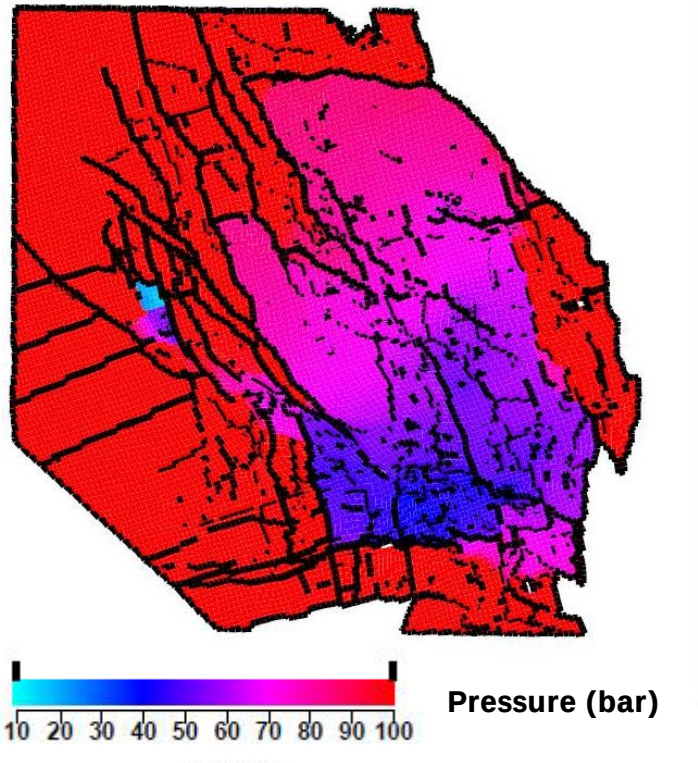




Buijze, L., van den Bogert, P.A.J., Wassing, B.B.T, Orlic, B. and ten Veen, J., 2017: Fault reactivation mechanisms and dynamic rupture modelling of depletion-induced seismic events in a Rotliegend gas reservoir. *Netherlands Journal of Geosciences* **96** (5) s131–s148. https://doi:10.1017/njg.2017.27

What do we (think we) know? (continued)

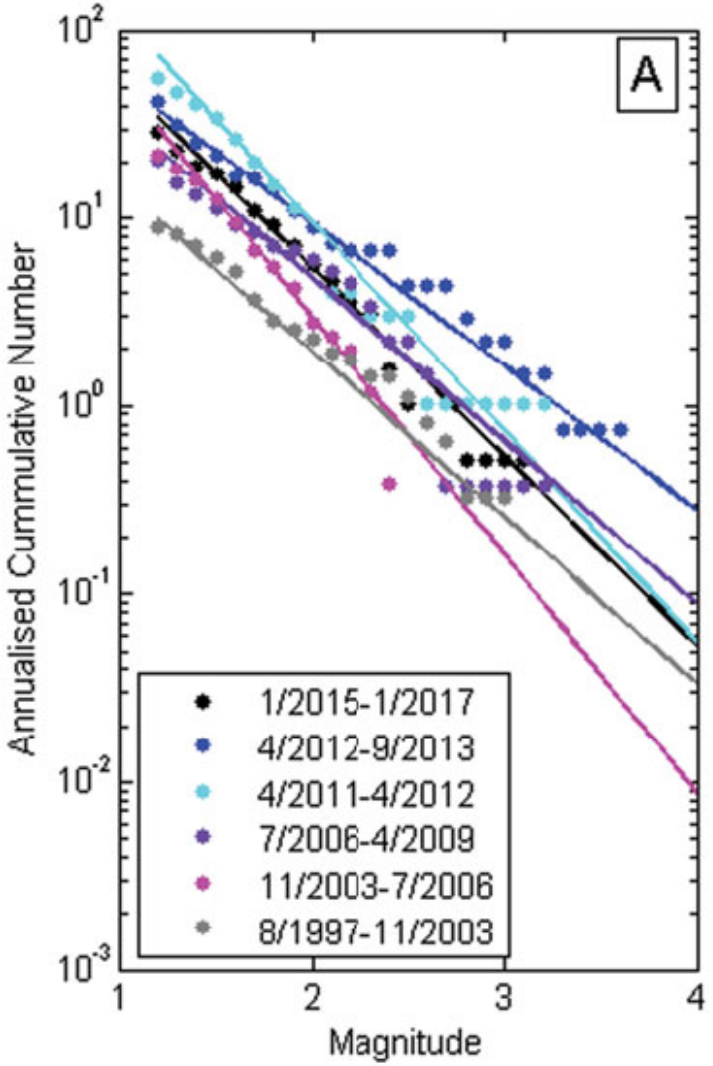
- Pressure is not evenly distributed (± 30 bar higher in N than in S)
- Pressure will equilibrate after several years if production stops => increase in S, decrease in N
- Pressures will continue to drop if production continues => Seisimicity will continue if production continues
- Average pressure can be kept constant by replacing produced volume, but local pressure differences will be present
- Earthquake rates reduce locally (and temporarily?) when production is reduced



Estimated reservoir pressure in 2021. Source: Technical Addendum to the NAM Winingsplan 2016

What are the key questions?

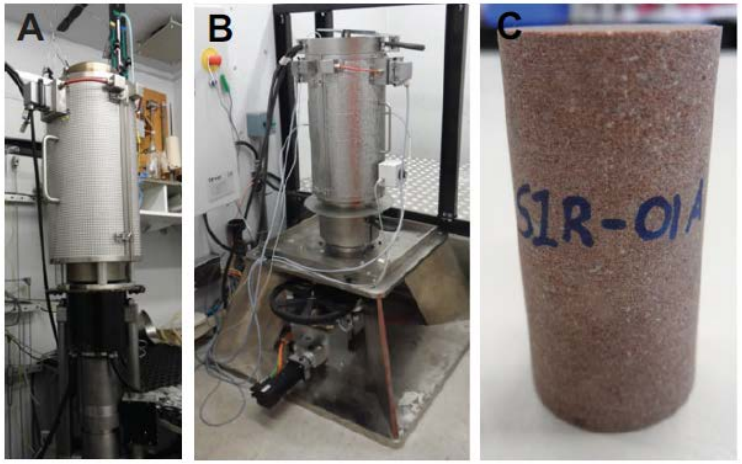
- Does a lower field production rate lead to **fewer** earthquakes for indentical production volumes? I.e. do we only “play the movie at a lower speed” or is there really a reduction in seismicity?
- Does a lower field production rate lead to a **different frequency-magnitude distribution** of earthquakes for indentical production volumes? I.e. to a change in *b* value in the Gutenberg-Richter relationship?
- Does “flat production” reduce seismicity?
- Do local production changes have a lasting effect or are they only temporary fixes?

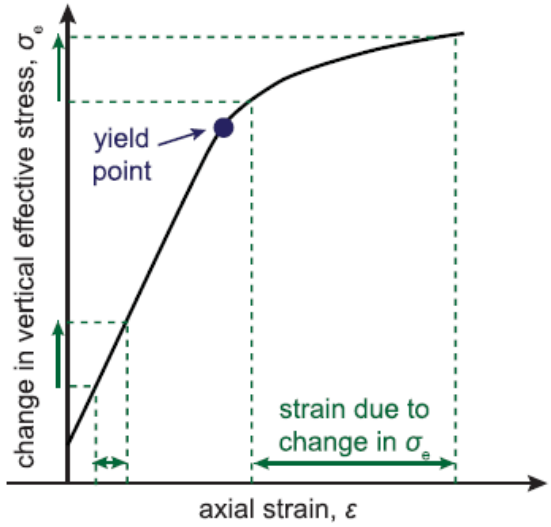


Frequency-magnitude distributions for different time periods. Source: Muntendam-Bos et al . 2017: NJG, 96 (5) s271–s278. https://doi:10.1017/njg.2017.29

What are the key questions? (continued)

- What are the physical mechanisms behind these possible beneficial effects? Creep (stress relaxation) in the rock inside/below/above the reservoir? Slow, non-seismic slip inside faults?
- First answers start to emerge from experimental work at UU:





Spiers, C.J., Hangx, S.J.T. and Niemeijer, A.R. 2017: New approaches in experimental research on rock and fault behaviour in the Groningen gas field. *Netherlands Journal of Geosciences* **96** (5) s131–s148. https://doi:10.1017/njg.2017.32

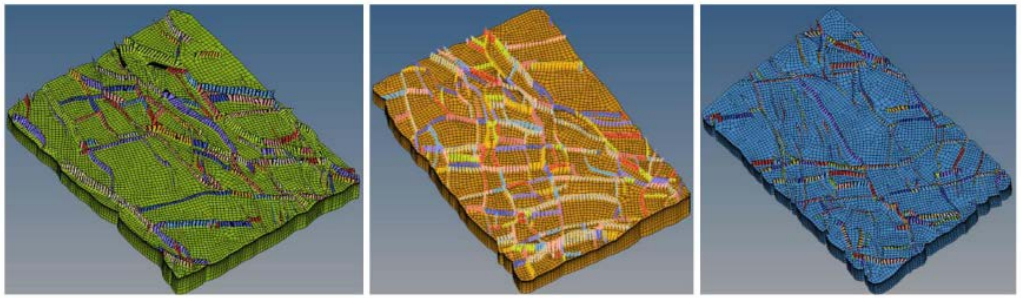
Many other questions

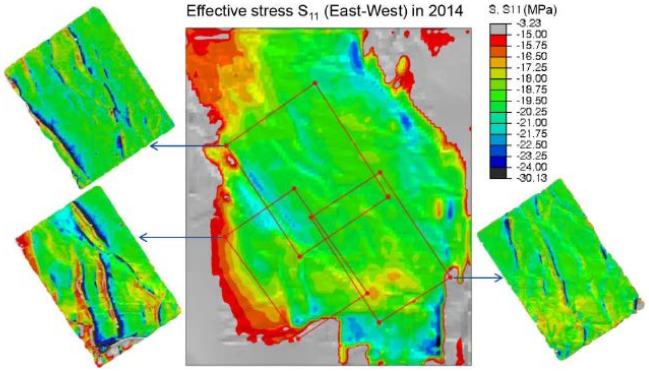
- What are properties in the deep and shallow subsurface that govern the wave propagation to surface? Heterogeneity? Soft soil properties? (“Ground motion prediction equation” GMPE)
- What is the relationship between small and larger earthquakes? Can we be warned by monitoring events? What if we detect also micro-events?
- What is the value of the current “measurement and control protocol”? Can we quantify its intended effect? And measure its actual effect? Could we do better?
- And many more…
- Note: many more questions are related to response of buildings and other surface objects, and societal aspect. Not covered in this talk which only considers subsurface aspects.
- **Ultimately: Can we quantify safety (and damage) hazards and risk? Can we control these?**

How to obtain answers?

- Current hazard and risk assessement based on a **probabilistic approach** (presentation Jan van Elk at this symposium)
- The underlying statistical concepts have been developed for natural earthquakes with (near-) **stationary** behaviour
- Induced earthquakes in Groningen are **transient** (i.e. non-stationary, over a period of decades)
- Changes in production strategy (total rate cuts, local shut-ins) make results even more **non-stationary**

Use a geomechanical approach?





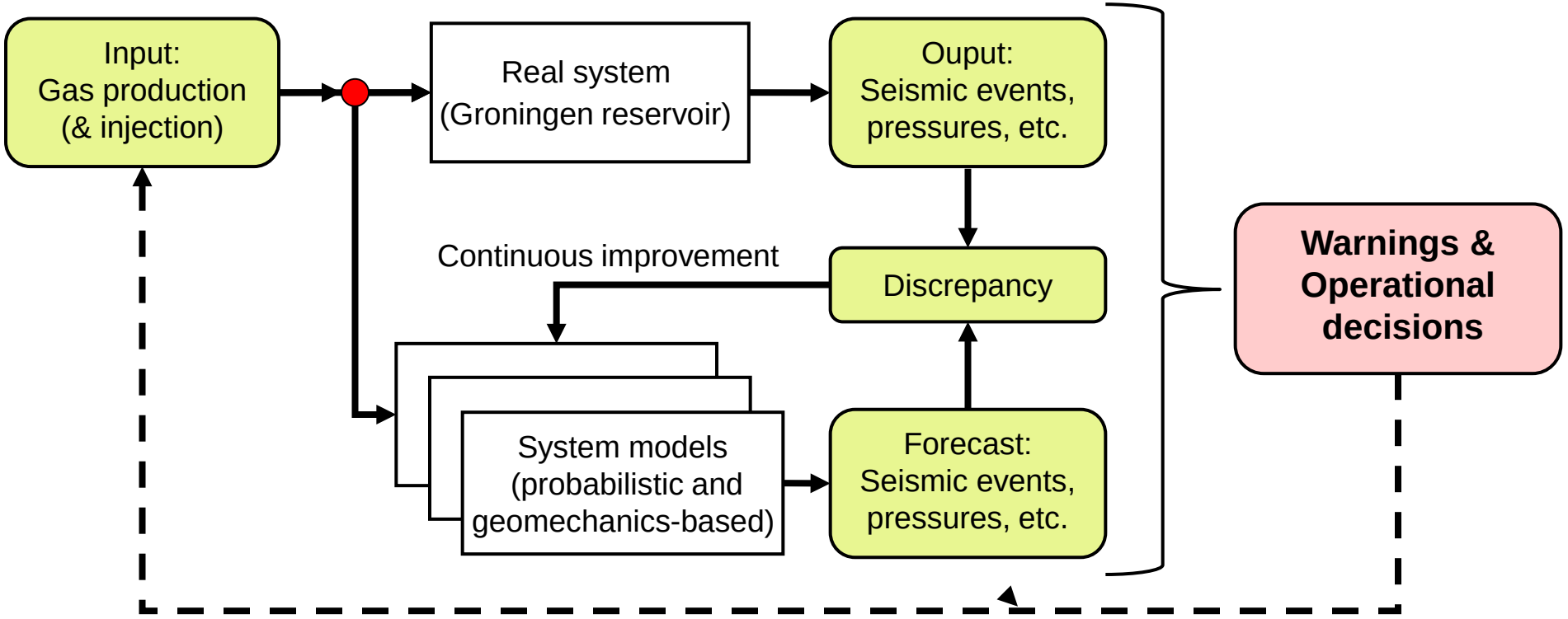
Source: Lele et al., 2016. Geomechanical modeling to evaluate production-induced seismicity at Groningen field, Proc. Abu Dhabi Int. Petr. Exhib. Conf. Paper SPE-183554-MS. Abu Dhabi, UAE

Value of a geomechanics-based approach

- Probabilistic approach: no **predictions**, only **forecasts**
  - Prediction: precise statement about the occurrence of an earthquake of a specific magnitude at a specific moment and location
  - Forecast: probability of occurrence of earthquakes in a given magnitude range within a given time window in a given area
- Geomechanics-based approach: most probably also no predictions but **better forecasts.** Sometimes even short-term warning signals (?)
- Has been tried (e.g., papers Exxon, TNO, Auckland, Stanford); **no good quantitative forecasts yet**
- Key uncertainties: **constitutive equations** (material properties): non-elastic stress-strain, fault friction, P and S wave velocity
- **Heterogeneities poorly known**, especially outside the reservoir
- Basis for **operational system** (like in weather forecasting)?

Operational system for forecasting and response

- Similar to systems used in weather forecasting



- Multi-scale, multi model
- Data-informed, probabilistic and geo models
- Ensemble-based to capture uncertainties

TNO?
KNMI?

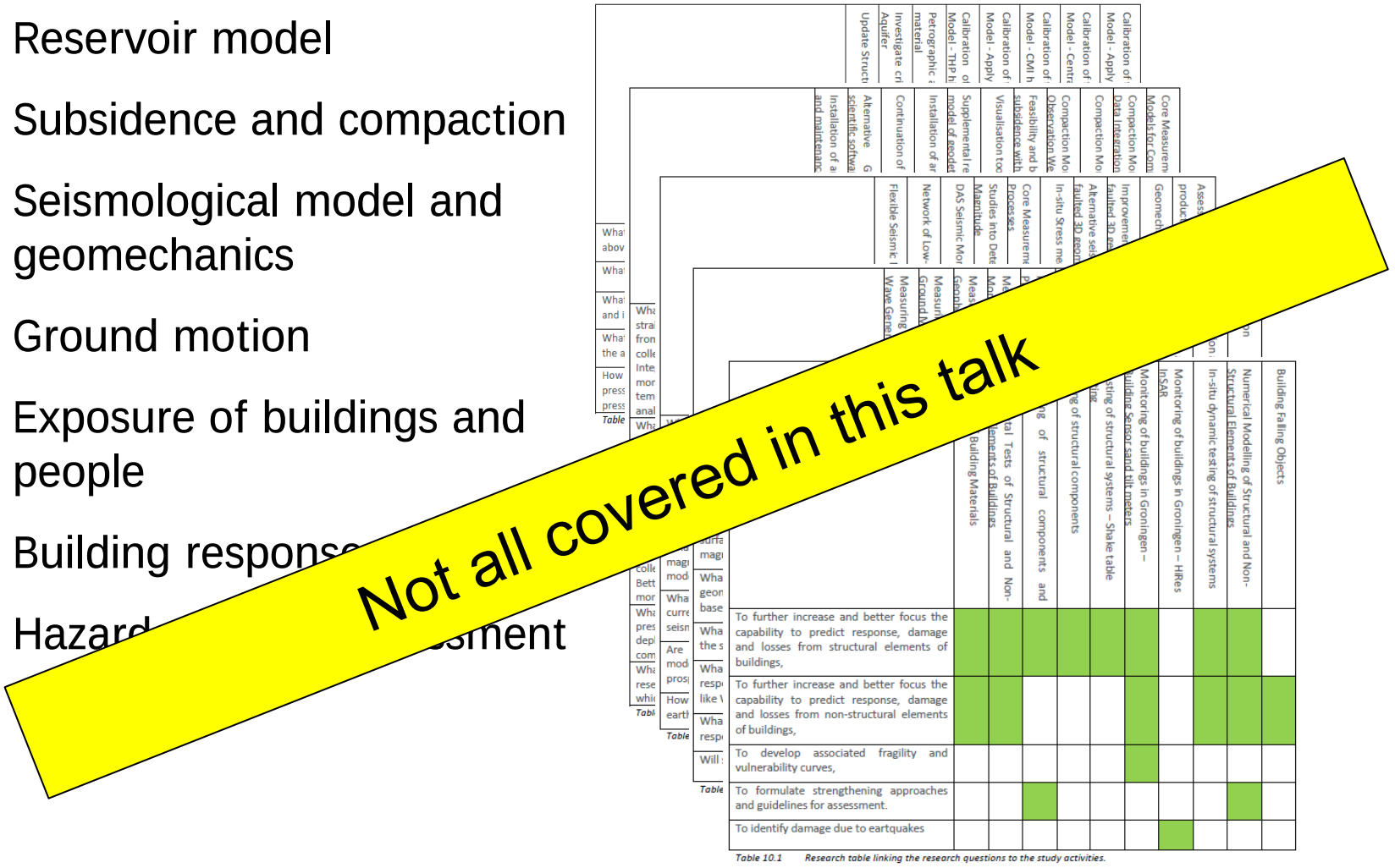
Open access!

Plans, programs opportunities

- 2013: KNMI/TNO/UU/TUD/RUG: National Induced Seismicity Program (**NISP**) presented to EZ for funding – no success
- 2015: **OVV report** – “structural and long-term research programme” needed. Recommendation endorsed by Parliament
- 2016: Ministry announces “Kennisprogramma Effecten Mijnbouw (**KEM**)” (Knowledge Program Effects of Mining)
- 2017: KEM operational – SodM in the lead. Mostly short-term research
- 2018: First call **Deep-NL** program: 7 million € for long-term research; mostly NAM funded; NWO-governed; total program 25 mllion € for 5 years.
- During all those years of ‘planning’, **NAM** has performed/commisioned a huge research program (100+ million €); some of it at Dutch and international universities. Also KNMI, TNO, CBS performed research

Further studies (NAM – post winnings plan)

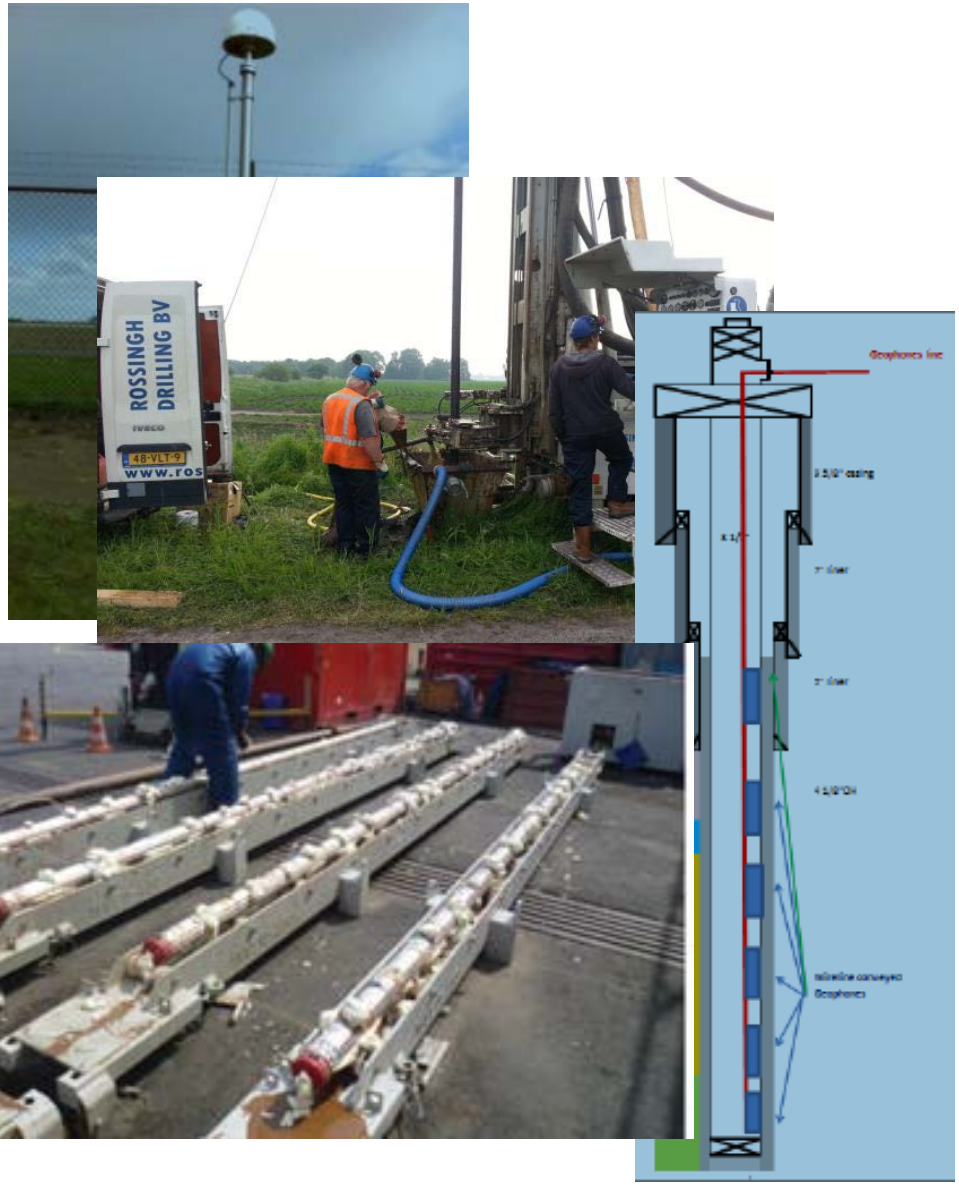
- Reservoir model
- Subsidence and compaction
- Seismological model and geomechanics
- Ground motion
- Exposure of buildings and people
- Building respons
- Hazard sment



Source: Study and data acquisition plan induced seismicity in Groningen–update post Winningsplan 2016, Parts 1 and 2. Report EP201604200072. Nederlandse Aardolie Maatschappij (Assen).

Key measurements (from NAM program):

- GPS stations (vertical and horizontal motions)
- Dense seismological network
- Deep arrays (borehole seismometers)
- Fibre-optic compaction measurements
- Cores from Zeerijp well
- Shallow S wave profiles
- Gravimetric survey
- Wireline logs
- Accelerometers
- ...



Conclusions

- Key subsurface research questions (in my opinion):
  - Lower production => fewer earthquakes or just a delay?
  - Lower production => different frequency magnitude distribution?
  - “Flat production” = > any benefit?
  - Measurement and control => can it be done?
  - Pressure maintenance => feasible option?
  - Monitoring micro-events => predictive value?
- Many more questions: subsurface, surface and society
- Probabilistic and geomechanics-based models needed
- Operational system for forecasting and response
- Competing theories: yes!
- Shared data bases; open access
- Translation of research for wider public