Subsidence and earthquakes of oil, gas and geothermal exploitation - guest lecture
Dar es Salaam Institute of Technology (DIT)

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Who am I?

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education

Dr. Robert Hack

- PhD University Delft: Engineering Geology
- MSc Engineering Geology (University Delft) & Applied Geophysics (minor, University Utrecht)
- BSc Geology (University Leiden)
- Chartered Engineer (UK)
- Member AEG (USA)
Track record:

- ITC/University Twente
- Grabowski & Poort Consultants
- Copper mines Zambia
- Ballast Nedam Contractors
- Boskalis Contractors
Who am I? - Work experience

- CO2 capture and sequestration (CSS)
- Environmental impact oil & gas industry, Netherlands
- Tunnel design & site investigation, Ukraine
- Underground mining, Zambia
- Slope design, Bhutan, South-Korea
- Foundation engineering, Middle East
- Railway bridges, Indonesia
- Pipelines, Saudi Arabia
- Causeway, Saudi Arabia, Bahrain
Who am I? - Research

- Determination and representation of uncertainty in engineering geological subsurface models
- Methodologies for integrated data handling in large civil engineering projects
- Three-dimensional effects of seismic waves on slopes
- Degradation of soil and rock mass properties in time (rock and soil mass weathering)
- Determination of discontinuity data by laser scanning (Lidar)
- Optimizing of the use of three-dimensional GIS and knowledge base systems for engineering geology
- Flood Control 2015 project that concerns developing a flood control system
- Dyke and dam stability from remote sensing
- Subsidence and earthquakes of oil, gas and geothermal exploitation
Contents

- Location
- Topography & land use
- History
- Going down through time – geological history
- Gas exploitation
- Subsidence
- Earthquakes
- Geothermal energy
- Shallow subsurface geology
- Water management
- Damage
Groningen

Province in the North of the Netherlands

With one of the largest gas fields in the world

Subsidence and earthquakes of oil, gas and geothermal exploitation
Topography

Subsidence and earthquakes of oil, gas and geothermal exploitation

(map courtesy Groningen provincie map, 2019)
Topography

- Allover Groningen is flat low lying area with mainly clay in the shallow subsurface in the North
- To the south are sand bodies
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Landuse

- Mainly agricultural area
- Quite old – already inhabited in pre-historic times
- Historical times from 6th century CE
“Wierden”, “terpen” (in English “mounds”)

Before the northern shore was protected by dykes, people lived on mounds; a mostly small man-made hill just above sea or river flood level (in Groningen “wierden”; in Dutch “terpen”). The mounds are still visible in the landscape.
Sea water protection - dykes

Nowadays the coast at the North is protected by dykes; as is the land along the rivers.
Why is there gas and where is the gas?

To be able to answer:
We drill a borehole below Slochteren
that brings us back in (geological) time

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Why is there gas and where is the gas?
Slochteren - Groningen

Slochteren
- center of the very large Groningen gas field
- discovered in 1959
Geology & geological history

(De Mulder et al., 2012)
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Geological Time

(drawing courtesy: USGS, 2019)
Why is there gas and where is the gas?

Geological history (2)
370 ma years

The bottom of the borehole is in Earth layers with an age of about 370 Ma (i.e. 370 million years in the past).

This does not imply that the geology before that time is not of interest but for the gas exploration geology it becomes interesting.
The Earth looked completely different from the Earth today.

Two continents had formed: Gondwana and Laurussia.

Parts of what later will be South-America, Africa, Antarctica, and India are part of Gondwana.

Laurussia contains large parts of what are to become Europe, Greenland, and North-America.

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370 Ma ago
Late-Devonian

Laurussia & Gondwana in the Late Devonian, 370 Ma ago (modified from Torsvik et al., 2014)
Devonian - Fishes and forests
419 to 359 Ma

- Large forests
- Fish and shellfish species in the seas
- First animals get on land

In the Silurian period, the time before the Devonian period, the first plants and arthropods (species of animals such as insects and scurps) came on land; before the Silurian the land was barren.
370-300 Ma

Variscan” or “Hercynian” Orogen

Gondwana and Laurussia collide and form the supercontinent of Pangaea.
Carboniferous – coal forming
359 to 300 Ma

- Very large lush rainforests
- Creeping and small animals (amphibians, very large arachnids (bugs) and insects)
- Highest ever oxygen levels (up to 35 % - present-day 23 %) – extensive forests (and bush fires)
The very large lush rainforests allowed for large quantities of dead organic material; the earth changed frequently with flooding of forests and deposition of sealing layers (prohibiting oxygen access and thus rotting) and thus creating peat that later became coal with time under pressure.
Carboniferous – Gas “mother” rock
359 to 300 Ma

The coal forming also produces large quantities of gases such as methane.

Methane is the main part of the gas produced in Groningen.
Glaciations started during the Late Carboniferous and continued into the Early Permian.

The Permian started as an icy tundra environment; later became warmer and more desert type environment.

Oxygen dropped to some 23% (about present-day level).

Mainly coarse- and fine-grained, clastic sediments ("sand and gravel"), and some evaporites (salts).

Amphibians and first reptiles.

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Permian – Rotliegend – Gas reservoir rock
300 – 260 Ma

The sand and gravel layers of the Rotliegend are porous and permeable and form the reservoir rock for the gas originating in the underlying Carboniferous.
Extensive deposition of evaporite rocks ("salt") in the Zechstein Sea

Permian – Zechstein
260 – 240 Ma

(drawing courtesy: https://soundwaves.usgs.gov/2044/02/permian-earth.giff)
Permian – Zechstein – Gas “cap” rock

- Salt is impermeable for fluid and gases
- Hence, salt is the *cap rock* for the gas trapped in the Rotliegend below
Permian – Triassic extinction event
252 Ma

- Reducing oxygen level, climate change, change in atmosphere, volcanic activity, and deadly anoxic event in the oceans
- At the same time, rising global temperatures, due in part to increasing quantities of CO2 in the atmosphere, also made for a stressful environment for many terrestrial Permian organisms
- Extension of very large quantities of species, 96% of marine species disappearing off the face of the Earth forever
- Terrestrial ecosystems also underwent a devastating series of mass extinctions, with over two thirds of all land vertebrates vanishing
**Triassic**

252 to 201 Ma

- Nearly all live extinct
- Barren landscape with sand deserts and salt lakes
- Deposits of sand, gravel, and salt
- First dinosaurs

(Salt mining in Twente is from the Triassic salt)
Jurassic - Cretaceous
201 to 145 (Jura) & 145 – 63 (Cretaceous) Ma

- Warming, high-oxygen level
- Reptile (dinosaur) time (“Jurassic Park”)
- Many places on Earth had a shallow, relative warm sea
- Extensive calcareous deposition (resulting in extensive calcareous rocks; limestone & dolomite deposits)
Pangaea breaks up
225 - 200 Ma

Pangea starts to break up into the present-day continents, including Africa and Eurasia (Middle-Triassic).

This breaking-up is still ongoing, for example, the North Atlantic Ocean spreads by about 25 mm per year.

- 175-145 Ma  Africa rotates clockwise and moves away from Western Eurasia, but later reverses and collides with Eurasia in the Alpine Orogeny.

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Alpine orogenesis

145 Ma-present Alpine orogeny:
Africa rotates anti-clockwise, collides with Eurasia and forms extensive mountain ranges, such as the Pyrenees, Alps, and Betics in Spain.

India collides with Laurasia and forms the Himalayas
66 Ma years ago impact of the meteorite or asteroid that created the Chicxulub crater in Mexico

Afterwards the Earth was a devastated area

The large reptiles became extinct and gave space for new life forms: the present-day living species
At the end of the Neogene (Tertiary) Groningen is at a slowly subsiding basin that is filled with the material of some large rivers (Eridanos, Rhine, and Meuse) (about similar to the present situation, except that the Eridanos does not anymore exists).

Eridanos was a very large river flowing from Northern Russia (size half of the modern Amazon)
- Time of the glaciations
- Groningen is covered at least two times by an ice sheet with a thickness of hundreds of meters (caused consolidation of surface ground)
- North Sea is dry during the glaciations
Quaternary - Holocene
< 11.700 year

- Climate change – warmer
- No glaciations
- Sea level rise – North Sea filled up

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Gas

The geology governs the presence of gas:
There should be:

▪ A “cap rock” (which seals it – Zechstein salt)
▪ A “reservoir rock” (where it is stored – Rotliegend sandstone)
▪ A “mother rock” (where it is formed - Carboniferous coal)
Gas (2)

The present-day gas thus is located in the billions of very small pores between the sand grains of the Rotliegend sandstone.

It is thus NOT in a big hole in the ground filled with gas !!!!!
Gas (3)

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Fault layout

(from Kortekaas & Jaarsma, 2018)
Geological model reservoir

3D view (from the SW) of the Top Rotliegend. Colors denote depth (red is highest), blue plane denotes the Gas Water Contact. Red lines denote wells. (from NAM Workshop, 2016)
Variation in reservoir constituents and facies

- It is **not** one and the same material
- **Different** layers with different material constituents (sand, clay, or salt minerals) and layers with mixtures of various minerals

Therefore:

Properties such as packing of grains, porosity, and permeability vary vertically and laterally
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Reservoir model with faults

Many faults in gas reservoir

Subsidence and earthquakes of oil, gas and...
Subsidence and earthquakes

Load of overlying ground is carried by grain skeleton, fluid and gas.
When gas or fluid is let out of the pores in the reservoir rock (i.e. the gas or fluid pressure is reduced):

- The skeleton of sand grains has to take the load originally taken by the fluid or gas
- Skeleton get under a higher stress (i.e. higher effective stress)
- Skeleton compresses (i.e. compacts)
- And thus subsidence at surface
Subsidence
Groningen field

City of Groningen

Subsidence and earthquakes of oil, gas and geothermal exploitation

(from TNO-NITG: http://www.natuurinformatie.nl/ndb.mcp/natuurdatabase.nl/000331.html)
Subsidence & Earthquakes (2)

- Many **faults** in gas reservoir
- Thickness of reservoir rock not everywhere the same
- Different compaction between different parts of the reservoir
- When fault contact between different reservoir thicknesses: fault may only move when certain shear strength is exceeded
  - > Earthquake
Geothermal Energy Applications
A wide variety of different use of the underground

Geothermal Energy systems

- Shallow
  - Ground Source Heat Pump GSHP
  - Boreholes Thermal Energy Storage BTES
  - Aquifer Thermal Energy Storage ATES
- Mid-deep
  - Low Temperature Geothermal Energy
  - High Temperature ATES
- Deep
  - High Temperature Geothermal energy
- Ultra Deep
  - UDG electricity production
  - Enhanced Geothermal Energy System (EGS)
No subsidence if water pressure in the subsurface is not reduced

Earthquakes possible if pumping out and injection of water give stress changes in reservoir rock and faults. Stress changes may allow shear stresses to release, in particular along existing tectonic faults under tectonic stress.
Shallow sub-surface geology

(Dinoloket, 2019)
Water management

- Subsidence causes that surface- and ground-water will be higher relative to the terrain surface
- Subsidence not everywhere the same
- Rivers and canals may start flowing in the opposite direction
- Bridges may become too low (clearance reduces)
- Dykes may become too low
Extensive water management program to counteract the effects of subsidence:

- **Extra pump capacity** to keep surface and groundwater on same relative level to the terrain level
- **Management of inverted** rivers and canals
- **Increase** of bridge heights (increase clearance)
- **Increase** dykes heights
Groundwater governs settlement of foundations of houses and other structures:

- Wooden pile foundations will rot when above groundwater level
- Reduction of groundwater level will give increase in effective (grain skeleton) pressure and subsequent settlement of foundations, in particular of foundations on clay and peat
Subsidence due to gas exploitation gives little or no damage (the subsidence is bowl-shaped over a very large area; hence \textit{differential subsidence} very small)

- \textbf{Earthquakes} may give direct damage by shaking object
- The ground in the shallow subsurface may \textit{resonate} with earthquake leading to more damage
Structure & foundation damage (2)

- Foundation problems may arise from **groundwater changes**
- Foundation damage due to earthquakes may be **delayed** when small cracks (fissures) are introduced in the ground and foundation; these may not immediately cause visible damage, but in time with creep effects may cause foundation and structure damage

- But also: many houses are **very old or of poor quality**, and are very vulnerable to earthquake damage
Load of overlying ground and structure is carried by grain skeleton, and fluids and gases in the pores (similar to compaction in gas exploitation giving reservoir subsidence)
Settlement (2)

When pressure of fluid and/or gas is reduced, more load has to be taken by the grain skeleton:

- The grain skeleton becomes compacted (also “consolidated”)

Compaction may be:

- **Elastic** (i.e. grains stay at the same place relative to each other)
- **Plastic** (i.e. grains displace and/or break and fill up the pores)
Layers with a very open structure (thus with large porosity), with a very weak grain material, or with very weak bounding between grains (cement):

- The layer may completely collapse when pore pressure is reduced; i.e. ‘pore collapse’

this may give a very large reduction in volume of the layer (‘collapsible soils’)

Settlement (3)
Settlement (4)

Expelling of water

Water in soils with:

- **high** permeability (e.g. sand, gravel):
  
  expelling of water is **fast** (instant), hence fast settlement

- **low** permeability (e.g. clay, peat)
  
  expelling of water is **slow**, hence slow occurring settlement (delay)
Old-fashioned foundations

- animal skins (to improve integrity of ground below foundation) (never found but rumored to exist)
- “huien” (to spread stress below foundation and to bring foundation load to a lower level below terrain level) (*)
- any rubbish (stones, waste and whatever else was available)
- wooden piles

* “huien” can be small diameter wooden piles, bundled in groups (with the name in old-Dutch of “huien”) or are a type of vessels such as for wine or beer without top and bottom, and filled with soil (Frans Barends)
Integrity – loss of structure

(from: http://www.nienhuys.info/)

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Integrity – loss of structure

In old structures of stones and timber often limited tensile strength between stones and between stones and timber elements, i.e. little of no cement or cement of poor quality, no tensile elements such as steel bolts and nuts, etc.:

- Stability of such structure depends on the structural integrity; i.e. it is a tight fitting arrangement of stones and timber elements
- Vibrations by an earthquake cause loosening and thus reduction of integrity
- Vibrations may cause small settlement in foundations
- Loss of integrity may cause cracks and instability
Integrity - rocking

Small vibrations may cause rocking of structure and foundations with settlement of foundations on perimeter of structure

- May cause tensile stress in center structure and crack

Subsidence and eart
Differential settlement

Effect of different depth of foundation

Cracks to top of structure

Tilting of front and back roof

Cellar

Small settlement

Larger settlement

Settlement

Cellar

(From: http://www.nienhuys.info/)
The external walls have a larger mass than the inside walls,

Soil pressure under center of building can only be released to the sides, but is restrained by outside walls

This causes both settlement and tilting outside of external walls

The building splits vertically, starting above the windows and door openings directly under roof line.
 Delay in settlement and creep in soil

- Peat and clay partially react on stress with delay (expelling of water after time)
- Vibrations may cause small cracks in soil (clay)
- Cracks allow water to be expelled slightly easier and faster
- Settlement after time

Thus if structure on different grounds, the ground may react with different delays (also named “different creep”); hence differential settlement and resulting damage in structure only after time
In the end many 1000’s damaged houses

(from: https://www.rtvnoord.nl/aardbevingen)


(http://www.gevel-ornamenten.nl/projecten.php?id=4)
Public & political response

What did local people notice:

- Booms and rumbling sounds
- Some small and limited damage

In first instance (for years) no link was made to the gas exploitation
Public & political response

Well known experts gave as opinion that it could not be due to the gas exploitation, because that was known to be only plastic deformation!

Alternative explanations were proposed:

- Shallow ground explosions by shrinking or expanding ground under influence of water or temperature changes
- Breaking of the sound (sonic) barrier by highly secret spy planes from the Americans (assumed the “Aurora” ultra-fast spy plane)
- People heard the television of the neighbors (possible movie “Earthquake” 😊)
Public & political response

However, booms and rumbling sounds and damage kept ongoing and became more and more………

A scientist at the Technical University Delft, did some numerical calculations and concluded that earthquakes could be the reason……

However, even within the university he was not taken seriously by many staff members.
Public & political response

The long denial of the gas exploitation as reason eroded the public trust in the government, gas company, and experts (also those of independent universities and research institutes)

But more and more prove for gas exploitation as reason

Resulting finally after years of discussion, that the government had to amid that gas exploitation was the reason
Public & political response

Now the earthquakes are generally accepted as reason and the government feels forced to reduce gas exploitation considerably or to stop altogether with gas production.

This costs:
- the government billions of euros per year in lost revenues
- but also the gas company
- repair works are going to cost billions
- and the confidence in experts is damaged (for a long time to come)
What do we learn from this?

- A situation develops that has never been encountered before
- It goes gradual and gradual changes are often difficult to identify

But what if decent environmental assessment had been done on forehand
• Exploration & Exploitation of natural energy resources always give environmental impact
• Risks may not always be fully anticipated
• Standards shift
• Environmental Impact often ‘closing issue’ on budget resulting in not enough budget to allow thorough evaluation

Legislation and regulation should be in place to enforce the environmental impact assessment and appropriate measures to be enforced by regulating office
In first instance most companies and government will resist but

- later many company and government experts admit that the assessment was useful (and helped convincing their management) that some more attention was required
- they had advice from independent experts
- the legal status forces the management and politics in accepting measures reducing hazards and risks

An Environmental Impact Assessment is a advantage not a hindrance
Therefore:

- Each project should be assessed on environmental impact
- Environmental impact assessment should be scrutinized by external and independent experts

Nowadays, in the Netherlands this is done by the “Commission on Environmental Impact Assessment” (MER)

The scrutinizing by the MER is regulated in law, and thus can be enforced
Time frame

- 1959 – discovery gas field
- 1963 – large-scale production of gas
- Late 1980’s – first notion about booms, rumbling sounds, and small damage to houses
- Early 1990’s – first scientific proof that earthquakes could occur due to gas production (Roest & Kuilman, 1994)
- 2000’s more and more serious damage to houses and houses with small damage start to fall apart due to loss of integrity
- 2000’s realization by government and gas producing company that a major problem was developing
- 2010’s serious public unrest
- 2018 considerable reduction of quantity of produced gas due to public pressure
- Ultimately 2030 altogether stop of gas production due to public pressure (about 40? billion euro worth of gas will be left in place)
Purely speculation

If in 1956 a Commission for Environmental Impact Assessment had existed, maybe none of the damage would ever have occurred:

▪ Possibly different production plan avoiding large compaction differences
▪ Avoiding compaction differences by injection gas (CO$_2$ or nitrogen)
References (1)
References (2)


