Compaction Risks

Maurice Dusseault
Reservoir Compaction

- Triggered by reduction in pore pressure
- Important drive mechanism in high $\phi$ cases (Maracaibo, Ekofisk, Wilmington, ...)
- But, problems develop with compaction ...
  - Casing collapse in the reservoir
  - Surface subsidence from deep compaction
  - Casing shears above the reservoir (Ekofisk)
  - Reservoir simulator predictions are contentious
  - Large stress redistributions, microseismicity…
The Case of Ekofisk

- 3000 m deep
- 7 km wide
- Very thick reservoir
- High porosity chalks
  \[ \phi \text{ from 25 to 50\%} \]
- Overpressured by 1.7
- Large drawdowns are feasible – large \( \Delta\sigma'_v \)
- Large compactions…
- Would we plan for these nowadays?
Compaction occurs whenever the net stress increases ($\sigma' \uparrow$, $\phi \downarrow$)

- Magnitude depends on the rock stiffness, fabric (some rocks have a quasi-stable $\phi$)
  - Important in high-porosity sandstones
  - Important in North Sea Chalk (e.g. Ekofisk)
  - Important in Diatomite
  - “Recompaction” is important in cyclic steam stimulation (porosity cycling)

- Geomechanics of compaction are fundamental to the risk management process
Bedding Plane Slip & Casing Shear

- Normal fault mechanism
- Low $\sigma_h$ region
- High $\sigma_h$ region
- High $\tau$ region
- Slip planes in overburden
- Compaction

Flanks -- shoulders -- crest -- shoulders -- flanks

Large compaction: seismicity, casing shear, casing bucking
Major Design Steps

- Identify physical compaction mechanisms
- Identify susceptible reservoirs
  - Based on experience in other reservoirs
  - Based on geophysical data (logs, seismics)
  - Based on core examination and lab tests
  - Based on geomechanics analysis
  - Based on monitoring information
- Study the cost-benefit gain to the company
- Implement mitigation measures in advance
Corporate Screening Strategies

Screening and Analysis

First-order screening (geology + cases)

Geomechanics assessment
- geophysical logs
- petrophysical evaluation
- stress history

Impact assessment
- reservoir modeling
- well modeling
- casing shear risk

Mitigation options
- pressure maintenance
- facilities redesign
- production strategies

Risk assessment
- second-order screening
- production predictions

Cost-benefit analysis

Monitoring cases

Decision making
- experience base
- learning and teaching

Cost of options
$ - ¥ - Bs

Is compaction beneficial?
Compaction Geomechanics – I

- Compaction = $f(\Delta\sigma_{ij}', E, \nu, \ldots)$
- Is $\Delta p$ always = $\Delta\sigma_{ij}'$?
- No, compaction is not uniform
  - $\Delta p$ is not uniform in reservoir
  - Overburden arching takes place
- Thus, compaction moves out from production wells, arching delays full $\Delta z$ development
- This can be simulated quite well, with coupled models…
Compaction Geomechanics – II

- Compaction and depletion will change both normal stresses and shear stresses.
- If a “sharp” gradient of compaction occurs, $\Delta \tau$ (shear stress) can be quite large.
- This can cause shearing, grain crushing, loss of cohesion, liquefaction (Chalk), etc.
- These factors affect the permeability, often negatively, but shearing can also increase $k$.
- It is essential to study case histories to assess these factors, even semi-quantitatively.
Reservoir Compaction

- Delay of compaction always occurs in early time, before $\Delta p$ zones intersect (aspect ratio)

Initially

After some $Q$

$\Delta p$ region

no $\Delta p$ yet

Arching means that compaction can be missed in early time!
Δz Delay Through Arching

Subsidence response is delayed

In this phase, $\Delta \sigma_v'$ is not equal to $\Delta p$

Drawdown zones

Arching occurs until drawdown zones interact at the reservoir scale

Overburden stresses “flow” around the $\Delta p$, $\Delta V$ zone

Compaction is impeded by arching during early drawdown
Full Compaction

This demonstrates that geomechanics must be incorporated in risk assessment in compacting and subsiding cases.
Reservoir Compaction

- Compaction sustains production, and can change the production profile substantially.

\[ \Delta \sigma_v = \Delta p \]

Cost-benefit analyses require compaction assessment.
Negative Effects of $\Delta \sigma'_{ij}$

- Productivity can decline with an increase in $\Delta \sigma'_{ij}$, both in normal and shear stresses
  - Fracture aperture diminution (+++)
  - Pore throat constriction (+)
- The relative importance depends on the rock mechanics properties of the reservoir
- Casing shear or buckling can occur
- Surface subsidence can take place
- These can be costly if unexpected. If understood, they are factored into risk study…
Casing Deformation

“Wedging”

Shear

Courtesy Trent Kaiser, noetic Engineering
Positive Effects of $\Delta \sigma'_{ij}$

- Changes in the effective stress can trigger changes in the porosity
  - Compaction can be substantial (UCSS, chalk)
  - Compaction serves to sustain the pressure
  - Much more oil is driven to the wellbores
- In high $\phi$ Chalk, a volume change as much as – 10% can take place, all oil production
- Compaction of high $\phi$ shales can also expel water into the reservoir, displacing more oil
Part of the risk assessment process for compaction and subsidence is assessment of reservoir compaction potential. This requires clarification of geological history and comparing the microfabric of the material to other known cases. Consult an experienced geologist for more help.

Solution and cementation reduce porosity, increase stiffness
Additional Mechanisms

- Compaction can lead to loss of some permeability in natural fractures, especially important in high $\phi$ fractured carbonates.
- Grain crushing can occur in some UCSS cases, therefore $k \downarrow$, reducing flow capacity.
- Depletion $\rightarrow$ loss of lateral stress, increase in mean $\sigma'$, increase in shear stress $\tau$.
- Increase in shear stress often causes $k \uparrow$ in jointed strata!
- Compaction can release fines from strata…
Fracture Aperture, $\Delta \sigma'$, $\Delta k$

- Fracture aperture is sensitive to $\sigma'_n$
- Permeability is highly sensitive to aperture
- Shear displacement and asperity crushing can develop with $\Delta \tau$

Reservoir engineers want a homogeneous constitutive macroscopic law linking $k$ to $\Delta p$. Really, a coupled geomechanics analysis is required, linking $k$ to $\Delta \sigma'$. 
Fracture Permeability Loss

- In many cases, fracture permeability decreases by a factor of 1.5 to 3
- This is a compaction effect (loss of aperture as net stress increases is a form of compaction)
- If we have folded or inclined NFCR’s, it becomes more complex: some fractures open, other fractures may close
- It is important in coal, North Sea Chalk, fractured gas shales, but not in sandstones
So, Compaction Risks Include:

- Casing shear and costly well re-drilling
- Platform subsidence offshore, ground subsidence onshore
- Induced seismic events (Ekofisk 2001 event, Wilmington 1953-1955 events)
- Unexpected production behavior
  - Compaction maintaining drive forces
  - Fractures closing or dilating
- And other effects…
Subsidence MacroMechanics
Predicting the Effects at the Surface and in the Reservoir
Consequences of compaction must be included $\text{-}risk$ analysis
Subsidence Magnitude

- If $W < Z$, arching, little subsidence ($<25\%$ of $T$)
- If $Z < W < 2Z$, partial arching (25-75\% of $T$)
- If $W > 2Z$, minimal arching ($>75\%$ of $T$)
- Bowl width: $L = W + 2Z\sin\theta$
- If $W > 2Z$, $\Delta z_{\text{max}}$ approaches $T$
- $\theta$ (angle of draw) usually 25 to 45 degrees
- In cases of complex geometry and stacked reservoirs, numerical approaches required
- Consequences: offshore or onshore??
Casing Impairment

- Either loss of pressure integrity, or excessive deformations (dogleg, buckling)
- Problem in massively compacting reservoirs
  - Compaction can distort and even buckle casing
  - Threads can pop open, casing can be ovalized
  - Triggering of faults shear casing which pass through
  - Overburden flexure causes shear planes to develop
  - Casings cannot withstand much shear
- These are vexing and difficult problems
- Is more compliant casing and cement best?
In compaction risk assessment, costs of casing shear are statistically included through a geomechanics coupled model.
Mitigation of Compaction Risks

- Pressure maintenance
  - Water injection or gas injection
  - CO$_2$ sequestration, and also used as an enhanced oil recovery approach (the future…)
- Structural design of platforms in offshore cases
- Repair and replace surface infrastructure
- Judicious placement of wellbore to reduce the incidence of casing shear
- Special completion techniques
- Monitor, monitor, monitor…
More Discussion of Ekofisk and Risk
Case Histories

- Maracaibo in Venezuela
- Groeningen in Netherlands
- Niigata in Japan (gas)
- Ekofisk in the North Sea (Norway Sector)
- Ravenna in Italy (gas)
- Many examples elsewhere as well
- Good examples in the hydrogeological and geotechnical literature are interesting
Hollow Coccoliths, Little Cement

Rock Mechanics Implications

- During development (1969-1975), engineers failed to predict massive subsidence.
- When noted in 1981-83, maximum subsidence was greatly underestimated (~6-7 m).
- Also, engineers failed for many years to understand the water-weakening phenomenon.
- Some consequences:
  - Platform jacking by 6.3 m in 1988-89.
  - Far greater OOIP and production rate.
Production-Injection History

Ekofisk Production & Injection

Reserves stb / boe
(100% @ 31/12/05)
In Place 6.7 Gstdb
In Place 10 Tscf
Produced 3 620 MBoe
Remaining 1 310 MBoe

Start water injection
Ekofisk (I)

- 3000 m deep Chalk reservoir, very thick
- Exceptionally high porosities, ~50% at the top, 30-35% at the base
- Overpressured, $\sigma_v = 65$ MPa, $p_o = 54$ MPa
- Moderate lateral stresses, extensional regime
- Chalk slightly cemented
- Overlying shales overpressured
- Large width with respect to depth ($W > 3D$)
- Water-weakening of Chalk promotes $\Delta z$
Ekofisk...

Reservoir structure

Porosity, $\phi \approx 50\%$ in this zone
Ekofisk (II)

- Lengthy well tests failed to detect compaction
- Subsidence assumed minor because of depth
- Casing shearing became a problem in 1980’s
- Wells had to be redrilled, some twice
- Subsidence first noted from platform legs
- 4.2 m in 1987, predicted max of 6.2 m
- Platforms raised, 1987 ($US485,000,000.00)
- Subsidence exceeded 6.0 m in early 90’s
Massive Reservoir Compaction

- Seafloor subsidence
- Leads to wave risks for platforms
- Casing shearing (some wells redrilled several times)
- Wonderful drive sustaining process!

1973

1984
Ekofisk (III)

- Redevelopment decision in 1994, $S = 6.4$ m
- Pressure maintenance tried in 1980’s, but it seemed quite ineffective, but in use now since 1988
- Repressurized since 1990’s
- More casing shear, most wells redrilled twice
- Numerical analysis showed 80-85% of compaction was appearing as subsidence
- Microseismic activity in overburden, along zones where casing was shearing regularly

2.3 billion $
Ekofisk (IV)

- However, it is a fabulous reservoir!
- 100% of initial predicted production was surpassed in early 1990’s!
- Life predicted to 2011, extended 30 years
- Some compaction drive continues ($\Delta z > 9$ m), but at $\sim 30$-35 cm/yr only
- Max $\Delta z$ now thought to be greater than 11 m
- Field may produce more than twice as much oil as initially thought!
- Ekofisk has been a major learning experience
Casing Shear at Ekofisk...
Ekofisk Continues ....

- Casing shearing not fully ceased or cured
- Will high-angle flank faulting develop?
- Redrilling wastes injection (Where? How?)
- Surface strains and subsea pipelines: will there be impairment of these facilities
- Oil storage facilities relocated?
- Can we reasonable predict these events?
- I believe petroleum geomechanics has advanced enough so that we can predict
Risk: Will the Reservoir Compact?

- All reservoirs compact, but how much?
- Best is to test truly undisturbed core samples in the laboratory under representative uniaxial and triaxial loading conditions.
- Failing this, a detailed comparison to other cases of compaction is carried out (logs, etc.).
- Predictions of compaction can be expected only to be +/-25% at best (sampling problems, long-term creep, etc.)
Risk: How Much Compaction?

- Depends on compressibility, Z, p, $\Delta p$, $\phi$
- Qualitative screening criteria (geology!)

- If porosity > 25% (> 35% is virtually certain)
- If the reservoir is geologically young (little diagenesis)
- If it is at its maximum burial depth (no over-compaction)
- If the mineralogy is arkosic or lithic (weak grains)
- If $\Delta p$ will be large, and particularly if overpressured
- Mainly in extensional regimes and continent margin basins
- If largely uncemented by SiO$_2$ or CaCO$_3$
- If reservoir width > depth to reservoir (no arching)
- Other criteria are probably of little relevance
Ekofisk and Valhall are similar Chalk reservoirs, formed because of deep-seated salt doming creating an anticline.

Prediction by Comparison

- Other case histories are carefully studied
- Quantitative comparisons are made:
  - Geological setting, thickness, etc.
  - Porosity from cores and density logs
  - Comparison of seismic velocities ($v_P$, $v_S$)
  - Study of diagenetic fabric and stress history
  - Geometry and scale of the reservoir wrt depth
  - Mineralogy and lithology of the sediment
  - Stresses, pressures, drawdowns, timing
  - Other factors?
- A probability estimate is made
You cannot manage risk properly without monitoring and use of monitoring data to update risk and cost assessment.
Mitigating Casing Shear Risk

- Stronger cement and casing are not useful
- There are several possible approaches
  - Pressure maintenance in the reservoir (H₂O)
  - Avoid placing wells in zones of high shear
  - Manage reservoir development strategies to reduce incidence: e.g. choose a lower shear stress method
  - Create a more compliant casing-rock system
- Avoidance & management require modeling
- Under-reaming & no cement delays distress
- Better sealing cements may reduce p migration
Simulation of Casing Shearing

Reservoir Scale Models

Component Scale
- Coupling
- Centralizer
- Base Pipe
- Cement
- Outer Casing
- Screen
- Gravel Pack

Near-Well Scale

Courtesy - TTI
Distortion of Casing
Mathematical Modeling of Strains
Under-Reaming to Reduce Shear

- sand stratum
- interface slip
- casing cemented, but not in the under-reamed zone
- shale stratum
- under-reamed zone
- bedding plane slip
Under-Reaming of Hole

Wilmington

- Unprotected Wells (155 total)
- 15" Under-ream (5 total)
- 26" Under-ream (147 total)
Analyzing Special Compaction Joints

Telescoping joint

Screen, basepipe, couplings

Sump packer

\[
\frac{\Delta H}{H} = \varphi C_p \Delta p \frac{1 - \nu}{3(1 + \nu)}
\]

for \( \nu = 0.2 \),

\( C_p = 9 \times 10^{-6} \text{ psi}^{-1} \)

\( \Delta p = 2600 \text{ psi} \)

\( \Delta H/H = 1\% \)
Compaction Risk Mitigation

- Good predictions are necessary
  - Geology, analogous cases, simulation, testing…
- Avoid compaction altogether?
  - It is a good drive mechanism, avoidance costs $$$
- Live with it, but be prepared
- Most important is to do our geomechanics right, and to examine the full spectrum of effects, negative + positive ones…