Petroleum Geomechanics

Examples where Geomechanics Knowledge is Vital

Maurice Dusseault
Petroleum Geomechanics Areas...

- Borehole stability (+ chemistry, diffusion, wellbore hydraulics…)
- Hydraulic fracturing (+ fracture and porous media flow of fluids & slurries, filtration…)
- Reservoir compaction (+ reservoir mechanics, geological history, mineralogy…)
- Sand production (+ capillarity, hydrodynamic forces…)
- Thermally-induced casing shear (+ thermo-dynamics, fluid flow…)

1-B Examples of Vital Geomechanics Knowledge
Coupled Problems…

- All these are coupled problems!

Solve a fluid flow problem to get a general pressure distribution, \( \{p\} \)

Pressures change stress so use \( \{p\} \) in a stress-strain (\( \sigma^\prime - \epsilon \)) problem

\( \Delta \sigma^\prime \) generates \( \Delta V \), so we have to put this back into the pressure solution

Reservoir Simulator for \( \Delta p & \Delta T \)

Continuum mechanics

Geomechanics Simulator for \( \Delta \sigma^\prime - \epsilon \) solution

Measurements for verification and model calibration

Diffusion mechanics
Three Chosen Case Histories

- Borehole Stability at Cusiana (Colombia)
  - $35,000,000 per hole before changes
  - $12-15,000,000 per hole after changes

- Compaction at Ekofisk-Valhall (North Sea)
  - Massive surface subsidence
  - Platform rebuilding as necessary, casing shear

- Casing Shear in Cyclic Steam (Canada)
  - Massive shear stresses from thermal stresses
  - Horizontal wells help solve the problem
Colombia Tectonics…

Massive Borehole Stability Problems

http://geology.about.com/library/bl/maps/blcolombiamap.htm

http://geology.com/world/colombia-satellite-image.shtml
The General Stability Problem...

- Cusiana Field, 4270 m, discovered in 1989
- In foothills just east of last major Andes range
- Lithology: alternating sand-shale sequence
- Tectonics: active faulting, overthrust belt, very high in situ shear stress at depth (near failure)
- 10 months drilling time, lost 20-30% of wells that were spudded, >10% of time spent on cleaning holes, expensive mud, stuck pipe, sidetracks, distorted casings, and so on
- $35,000,000 per well in 1990-1992 period…
The Geomechanics Problem

- Very high stresses *in situ*
- Relatively weak rocks (mechanical weakness)
- Fissile shales dipping at up to 30-40°
- Inclined joints and fissures that can slip if the MW is too high, creating hole constrictions
- These issues led to the problems observed:
  - Massive breakouts, sloughing, hole enlargement
  - Oil-based muds not effective (ie: natural fractures)
  - Stuck pipe from joint displacements
  - Hole cleaning problems, tripping problems…
**Stresses...**

![Map of Colombia indicating major stress directions and types of stress faults encountered.](image)

Borehole Stability…

- Borehole management involves not only stresses, rock strength, MW, mud type…!
- It also depends on hydraulics & chemistry:
  - Pumping strategy and cleaning capabilities
  - Gel strength, viscosity, mud density, filtrate chem.
  - BHA design, ECD, even tripping policy
HOW DO WE REDUCE ECONOMIC RISKS IN DRILLING AT CUSIANA?
Massive Subsidence - Ekofisk

- Huge reservoir, over 300 m thick in center
- High porosity (high-\(\phi\)) Chalk (see next slide)
- Oil production causes:
  - Drawdown of reservoir pressure – \(p\)
  - Increase in effective stress – \(\sigma'\)
  - Collapse of high-\(\phi\) Chalk to a lower porosity
  - Massive reservoir compaction (> 9 m at present)
  - Seafloor subsidence (>8 m at present)
  - And - good reservoir drive energy!
Coccolithic Structure of Chalk

Hollow Coccoliths, Little Cement

Ekofisk...

Reservoir structure

Porosity, $\phi \approx 50\%$ in this zone

Subsidence bowl

10 km

Tight zone

Type Well 2/4-C09

(porosity log)
Ekofisk and Valhall are similar Chalk reservoirs, formed because of deep-seated salt doming creating an anticline.

Massive Reservoir Compaction

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

1973

1984
Casing Shear at Ekofisk...

Source: EPOKE, Phillips Petroleum, No 7, 1999

Distribution of overburden shear damage and producing interval compaction damage at Ekofisk (SPE 71695)
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
- Complete platform redevelopment in 1999-2002
- Far greater OOIP and production rate
Production-Injection History

Ekofisk Production & Injection

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

Start water injection
But…

- Ekofisk taught us a great deal…
- The need for very careful rock testing under *in situ* conditions without altering the material
- Links between rock behavior, capillarity, chemistry and fluid flow ($\Delta p$) are important.
- Coupled modeling is needed for realistic predictions in reservoir geomechanics
- Measurements are always important
- Risks can be reduced by careful geomechanics
- There will always be some surprises!
HOW DO WE MANAGE ECONOMIC RISKS BECAUSE OF SUBSIDENCE AT EKOFISK?
Casing Shear in Thermal Projects

- High temperature ($T_o \sim 25^\circ C$, $T_i \sim 225-325^\circ C$)
- Large degree of thermal expansion of the sand reservoir that is convectively (flow) heated
- This also leads to thermal dilation of the sand, giving a large volume increase (1-3%)
- Overlying shale does not increase in volume (conductive heating is slow, no dilation)
- This means a great deal of *shear stress* is concentrated at the *sand-shale interface*
- Cased wellbores cannot withstand this (shear)
Imperial Oil – Cold Lake

Mega-Row CSS

Vertical displacements (mm) over 86 days

mod. Stancliffe & van der Kooij, AAPG 2001
Thermally-Induced Shear…

Shale: impermeable, stiff

Sandstone, permeable, softer

Note: casing experiences substantial distortional loading far in advance of the arrival of the thermal front. Largest shear stresses probably coincide with the thermal front.

thermal front, $\Delta V$ - expansion

displacement pattern

ovalization and collapse tendencies near interfaces (large stress concentrations)

dogleg over an interval

Shale: impermeable, stiff

Shale: impermeable, stiff
Thermal Compaction as Well…

Lost Hills, California
Δz Interferogram

Subsidence Induced Fissure

Courtesy: Michael S. Bruno
HOW DO WE MITIGATE ECONOMIC IMPACTS OF CASING SHEAR?
Exercise... Three separate groups...

- Each group develop a list of strategies for managing the risk associated with...
  - Group 1: Borehole instability, high stress area
  - Group 2: Massive subsidence, offshore field
  - Group 3: Casing shear, thermal project

- Write down your choices, we will present them and discuss them briefly...
Cusiana and Borehole Stability

- Choice of inclined well trajectory to penetrate shales at 90° (±15°), in the optimum direction
- Additives to plug induced shear fractures and delay hole sloughing behavior
- Careful mud control
- Change casing points
- Better hole cleaning & hydraulics to cope with the large sloughing
- Etc.
The Risk Minimization Loop…

- Interpretation of Drilling Mechanics
- Interpretation of Downhole Measurements
- Compare Realtime and Predrill Models
  - Continue Drilling
  - Agree?
    - YES
    - NO
- Knowledge Capture
  - Change Drilling Program
  - Alter Drilling Practices
- Models Calibration

Now at Ekofisk…

- Water injection is sustaining the reservoir pressure. This reduces but does not eliminate the reservoir compaction.
- Wells are drilled and equipped with more compliant casing so that more shear distortion can occur without shearing or breaching.
- Measurements: seafloor gauges, logging, etc.
- Better modeling and therefore predictions.
- However, Ekofisk made us humble! We did not predict its behavior in advance!
Handling Casing Shear

- Mitigation strategies include:
  - Adjusting well trajectories (avoidance)
  - Adjusting injection/production strategies
  - Modifying hole size and cementing practice
  - Changing casing grade (D/t ratio)
  - Changing inner completion design
  - Accept damage risk and adjust economics
  - Accept risk, design for easier re-drills, repairs…

- Geomechanics analysis helps quantify risk…
Risk Mitigation in Casing Shear

- Analytical Analysis Tool
- Reservoir Deformation Estimate
- Well Performance Comparison Tool
- Well Deformation Limits
- Common Design Analysis Database
- Simple Decision Analysis Tool
- Proprietary Decision Analysis
- Proprietary Reservoir Analysis
- Proprietary Well Damage Analysis

Optimum Well Design

1-B Examples of Vital Geomechanics Knowledge

Courtesy: Michael S. Bruno
Surface uplift / tilt data
reservoir inversion grid with 50x50m grid cells

Less well shear because of well trajectories!

ref. Nickle’s New Technology Magazine, Jan-Feb 2005
Lessons Learned…

- In many instances, geomechanics knowledge is vital to oil and gas development
- Borehole stability (Cusiana example)
- Subsidence (Ekofisk example)
- Casing shear (Oil sands Cold Lake example)
- And many others…
- These are “coupled” problems (combined stress-flow problems – Δp, ΔT, Δσ)
- Implementing geomechanics into planning reduces risk, avoids problems, lowers costs…