Geomechanics Assessment of Depletion (and Injection) Induced Changes: Risks of Reservoir Compaction & Subsidence, Well Integrity, Fault Reactivation & Earthquakes

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AOG Conference
Perth, West Australia
23 February, 2017
Definition of Geomechanics

- Geomechanics is the study of Earth stresses and mechanical properties of rocks at their current states, their changes and their effects
  - Present-day geological structures (folds, faults, fractures, etc.) are the consequence of the past stresses which may not be active today
  - Oilfield operations, and hence behaviour of reservoir and cap rocks, faults, etc. are strongly influenced by the present-day stress state

- Geomechanical modelling is therefore the basis for understanding rock behaviour and developing solutions for drilling, completion, stimulation and exploitation of conventional & unconventional reservoirs: to avoid hazards, increase efficiency and optimize production, safely and economically
Where and When is Geomechanics Needed in Oil Fields?

..... From appraisal-to-abandonment
..... 1D to 4D and well-to-field applications
Geomechanical Modeling, Workflow and Input Data

Drilling & Production Data
mud weights/ECD, survey, drilling history & events, XLOT/XLOT, Pp data, DST, production info

Core Data
Routine & SCAL
UCS, TWC, PSD, thin section, SEM, dispersion, chemical

Well Logs
Caliper, Gr, Rhob, Acoustic, image, NME, dipmeter, MWD/ LWD

Geophysical & Petrophysical
Seismic, Tectonic history, sediment., analogs, etc.

Geomechanical Model
stress magnitudes & orientation, pore pressure & rock strength

Update the model with new data

Pp Prediction
Hydraulic fracturing & Injection

Wellbore Stability

Sanding Prediction
Compaction & Subsidence

Fault seal & Fracture Permeability and Seismicity

Field Development and Reservoir Management

Stress changes with depletion & injection

Field Development and Reservoir Management
Depletion Effect on Stresses – Reservoir

- In the reservoir section, the magnitude of the horizontal stresses reduces as the reservoir depletes.
- For a laterally long layer-cake homogeneous reservoir the “stress path parameter” \((\Delta S_h/\Delta P_p)\) can be determined from poroelastic equations or field scale numerical modelling, both require calibration with field data.

\[
\frac{\Delta S_{h,H}}{\Delta P_p} = \alpha \frac{(1-2\nu)}{(1-\nu)}
\]

Stress profile of infill wells after depletion.

Fracking data (*) showed that stress path factors varies in different locations of the field.
Potential Depletion Effect on Reservoir and Overburden

- Fault reactivation due to Depletion
- Reservoir compaction, surface subsidence
  - compression and shear damage within production interval
  - shearing at the top of production/injection zones
  - localized horizontal shear at weak lithology interfaces within the overburden

After M.B. Dusseault et al. (2001)
Casing Shear: Causes, Cases, Cures
Casing Damage from Compaction

Example casing deformation patterns from Ekofisk Field (SPE 28091)

~10m compaction, ~3.7m surface subsidence
Example of Subsidence - Ekofisk, North Sea

Cost estimate:
“...Due to sea bed subsidence, the Ekofisk complex in the North Sea was sinking by approximately 40cm/yr and had reduced the safety air gap of 20m to 16.3m between the platform decks and storm waves. In order to compensate for the subsidence of six platforms, the ‘jack up’ project was born with a criteria to create a 23m 100 year ‘design wave’ by extending the platform legs and raising the decks 6m. This was the largest lift and most prestigious project in the world at the time with a total value of £400 million, and for IMH Commissioning Engineers the most challenging and rewarding undertaken at that time...”

Compaction and Subsidence can be predicted and modelled with a reasonable accuracy
Model Calibration for Subsidence and Compaction

Subsidence (surface data)
- Onshore, subsidence can be calibrated with surface data (GPS, InSAR monitoring...)
- Offshore, regular bathymetric surveys or platform positioning (GPS, InSAR)

Compaction (downhole measurements)
- Compaction calibration requires downhole measurement.
- CMI - radioactive bullet placed in the formation with regular spacing.
- Sureview Wire monitoring - optic fibers clamped on a casing
Real Time Compaction Monitoring (RTCM)

How it Works:

- Thousands of Fiber Bragg Grating on a fiber
- Each FBG responds individually to strain
- Software combines the information and creates a 3D image
- Directly measures axial strain, radius of curvature of bend and crushing
- Characteristic response differentiates the mode of deformation
  - Axial compression (compaction) & tension
  - Bending, Ovalization, Shearing

Figure 8. Unique signatures are seen for a) pure axial strain, b) bend or buckle, c) and shearing.
Modelling of Compaction and Subsidence
Case Study from South East Asia

- Business motivations:
  1) Loss of permeability due to pore collapse
  2) Platform subsidence
  3) Fault permeability after depletion / re-injection

- 8 major reservoirs are constrained with 3 major faults.
- 6 individual structural models are available for the reservoir sections.
- R6 has been in water/gas injection for EOR since 1994.
- R4 and R5 are planned to be injected for EOR from 2017.
Simulation Results: Compaction and Subsidence (strain)

- Longitude section (B-B)
- Map view
- Total subsidence
- Compaction of individual layers with depletion and injection

*All vertical scales x10 exaggerated*
Casing Deformation Simulation - Depleting Reservoir

- Local submodel are built along the actual well trajectories based on the casing string design.
- The pore pressure and displacement obtained from the 4D dynamic model are used as boundary conditions for driving the casing deformation simulation in the submodel.
Casing Deformation with Depletion

Original Location

Highest stress exceeds the casing yield stress.

P110 casing
Yield Strength
~758.5 MPa

31 Dec 2035

The modelled highest stress will cause less than ~0.5% plastic strain at the end of field life. If this level of plastic strain is allowable, the current casing rating would be safe during the production.
Fault Reactivation and Seismicity Due to Excessive Injection

Oklahoma’s recent earthquakes are associated with saltwater injection (disposal of produced water from oil wells)

- Increase of seismicity follows 5-10 fold increase in rates of water disposal
- The disposal formations are connected to active faults in crystalline basement.

Map of Earthquakes & Injection in Oklahoma

From Walls & Zoback 2015
4D Geomechanical Modelling of Fault Stability
SAGD Example, Canada
Tau Ratio (Cap Rock Integrity)
Future Applications: Earthquake Hazard Risk Assessment

**Challenges:**
- Events with low probability of occurrence and extreme outcomes – **Earthquakes**
- Uncertainty and complex, highly non-linear relationships in often data sparse environments
- ... *complex systems almost always fail in complex ways...*

**Solutions:**
- Develop a robust understanding of relevant data
- Enable access to data and visualisation
- Target data collection to improve reliability
Acknowledgement

My colleagues at Baker Hughes:
Dr. Ahmadreza Younessi
Dr. Ramon Guises
Dr. Feng Gui
Dr. Adrian White