Geomechanical Modeling of Stresses Adjacent to Salt Bodies: Poro-Elasto-Plasticity and Coupled Overpressures*

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Abstract

We predict how stresses and pore pressures evolve in the sediments bounding a salt body using coupled geomechanical models. We show that salt relaxation alters the stress state in the wall rocks and can induce pore pressure perturbations that extend kilometers away into the sediments. The time scale of dissipation of these perturbations is on the order of millions of years, suggesting that pore-pressure anomalies should commonly be present in mudstones near salt systems. Because previous models have not coupled changes in the stress field to changes in the pore-pressure field, they are unable to predict the interdependence between pore pressure and stress. However, accurate estimation of both stresses and pore pressures is critical to well-bore design. We employ a poro-elastoplastic soil model (Modified Cam Clay) and study how different drainage conditions affect the changes in strain, stress and pore pressure. We show that in drained systems, stress perturbations can generate low least principal stresses and a small drilling window (the difference between least principal stress and pore pressure) beneath salt. In contrast, in undrained systems, underpressures can lead to a relatively large drilling window, coupled with a significant decrease in pore pressure. These results may provide insight into pressure perturbations that have been encountered in deepwater drilling near salt. Coupled poromechanical models such as the ones discussed have the potential to illuminate how deformation occurs and predict stress and pore pressures in salt systems around the world.

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Reference


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**Jackson School of Geosciences**

**Geotechnical Group at MIT**
(Modified Cam Clay subroutines)
Estimation of stresses and pore pressures around salt

Hudec & Jackson 2006
Estimation of stresses and pore pressures around salt

Lower pore pressures
Drop in minimum principal stress
Narrow window between pore pressure and minimum principal stress

Rohleder et al., 2003

Hudec & Jackson 2006
How to calculate stresses and pore pressures?

Usual assumptions:

**Vertical stress:**
- Overburden

**Horizontal stress:**
- Empirical ratio

**Pore pressures:**
- Assume from analogous well
- from seismic
- from basin models

**Material:** Assume elastic
In this work:

*More realistic sediments:*

Model pore space, permeability

Elasto-plastic sediments

Stresses and pore pressures *calculated* through the *coupled* analysis
Why may pore pressures change?

Applied load shared between soil skeleton and pore fluid

Loading $\Rightarrow$ overpressures $\Rightarrow$ fluid flow $\Rightarrow$ back to hydrostatic

Duration of load application vs. time needed for dissipation:
- Loading much slower: pore pressures remain hydrostatic: \textit{drained}
- Loading much faster: overpressures develop: \textit{undrained}
Study: Porous geo-mechanical approach

ABAQUS™
Axisymmetric model
Uniform far-field loading: \( \sigma'_{h} = 0.5 \sigma'_{v} \)
Viscoelastic salt
Poroelastoplastic sediments (Modified Cam Clay)
Pore pressures remain hydrostatic
(Drained analyses)
Deformation pattern of relaxing salt

*Salt deforming to achieve isostatic state*

*Spherical salt flattens and bulges at circumference*

*Significant changes in mean effective stress*

*Salt deforming to achieve* isostatic state

*Change in mean stress relative to initial stress at flank*

*Spherical salt flattens and bulges at circumference*

*Significant changes in mean effective stress*
Stress changes around salt

No empirical stress ratio can apply
Overpressures develop
(Undrained analyses)
Development of excess pore pressures

Salt deforming to achieve isostatic state

Change in pore pressure relative to initial stress at flank

Pore pressure changes due to salt deformation:
Excess pressures at flank; Under-pressures above & below salt
Pore pressure perturbations extend km into the sediments
Drilling implications: salt flank

Drained:
Wider window between pore pressure and minimum principal stress
Drilling implications: salt flank

Undrained:
- Window narrows above and below salt flank
- Window shifts at higher pressure levels (*Blow-out risk*)
Drained:
Small window between pore pressure and minimum principal stress
Drilling implications: through center of salt

Undrained:
Sudden pressure drop (*Lost circulation*)
Time required to dissipate from Undrained to Drained?

Drained and Undrained: two limits of behavior

Transient behavior from theory of consolidation

Characteristic material property: *coefficient of dissipation*

For basin sediments: \( c_v = 10^{-8} \text{ m}^2/\text{sec} \)

Characteristic salt relaxation time: 10-100 years
Key points
Key Points

Salt deformation

UNDRAINED

DRAINED

Large pore pressure and stress changes

Million Years

Extend km into the sediments

Overpressures result in:
- Shift of the safe mud window to higher pressures at the salt flank
- Sudden pressure drops at top and base of salt
Key Points

Simple geometry, loading due to salt relaxation:
- Component of pore pressure due to deformation
- Better insight into sediment behavior

Eventually, combine with pressures and stress states from basin modeling and modeling of salt emplacement
Thank you!

Submitted to AAPG Bulletin:
Nikolinakou et al.: Geomechanical modeling of stresses adjacent to salt bodies: 2. poro-elasto-plasticity and coupled overpressures
Most common criticism:

A static model where system is relaxed does not represent the Earth

From a mechanical point of view, stress/pressure changes due to deformation is one component of overall behavior
Development of excess pore pressures

ELASTIC

ELASTOPLASTIC

Mean stress decrease

Mean stress increase

Underpressure

SALT

Excess pore pressure

Mean stress decrease

Underpressure

SALT

\( \Delta \sigma / \sigma_{v0} \) flank

\( \Delta u / \sigma_{v0} \) flank

Scale: 1 km; vex=1

Color Scale: 0 to 30%
Development of excess pore pressures

Pore pressure – mean total stress

Change in mean effective stress
Elastic vs. elastoplastic stiffness

Graph showing:
- Shear stress changes $|\Delta q|$ (MPa) on the y-axis.
- Horizontal strain (%) on the x-axis.

Key points:
- **Poro-Elastic** line.
- **Poro-Elastoplastic** line.
- Marked points indicating **less strength** and **more deformation**.

**Note:** X-axis labeled as **at salt flank**.