

Numerical geomechanics: advancing oil and gas exploration and production

Maximilian Haas

Geomechanics Centre of Excellence, SLB, London, United Kingdom, mhaas@slb.com

ABSTRACT: Numerical geomechanics has become an essential discipline within the oil and gas industry, enabling the prediction and management of subsurface behavior to optimize exploration, development, and production. By leveraging advanced computational techniques, numerical geomechanics integrates principles of rock mechanics, fluid dynamics, and material science to address challenges associated with reservoir deformation, wellbore stability, and hydraulic fracturing. This study presents a comprehensive analysis of theoretical frameworks and practical applications of numerical geomechanics, with a focus on finite element and finite difference methods for simulating complex subsurface environments. Key examples discussed include the integration of 3D and 4D geomechanical models to assess reservoir compaction and surface subsidence in mature fields, as well as predictive modeling of induced stresses and fault reactivation during unconventional resource development. The role of coupled geomechanics-flow simulations in managing water injection projects and mitigating risks in carbon capture and storage (CCS) will also be highlighted. Practical case studies are drawn from international projects, including a high-resolution geomechanical assessment from Middle East reservoirs, where advanced modeling techniques provided critical insights into fracture development and optimization of production strategies. Another example involves the evaluation of wellbore stability in deepwater environments, illustrating how numerical simulations mitigate drilling risks and enhance operational efficiency using the critical state method. Theoretical advancements in constitutive modeling and failure criteria are further discussed, emphasizing their importance in improving the accuracy of predictions under complex in-situ stress conditions. Practical considerations, such as model calibration using field data and real-time monitoring integration, are addressed to bridge the gap between simulations and field implementation. This work underscores the transformative potential of numerical geomechanics in addressing the industry's evolving challenges, fostering sustainable development, and ensuring the safety and efficiency of oil and gas operations.

KEYWORDS: Numerical geomechanics, finite element method, reservoir geomechanics, oil and gas.

1 INTRODUCTION

Reservoir geomechanics has emerged as a decisive discipline in the oil and gas industry, underpinning safe, efficient, and economically optimized field development across the entire asset lifecycle. By integrating advanced numerical modelling with field-scale data and engineering insight, geomechanics enables a quantitative understanding of the mechanical behaviour of the subsurface under complex production, injection, and stimulation conditions. This capability is vital not only for conventional hydrocarbon projects but also for emerging energy transition applications, where fault stability, fracture propagation, and reservoir containment are critical for long-term operational success.

Finite Element Modelling (FEM) serves as a cornerstone in this domain, allowing precise simulation of stress-strain responses at multiple scales: from the near-wellbore environment to field-wide coupled reservoir-geomechanical geological settings. Near-wellbore geomechanics is particularly crucial for designing robust well architectures, predicting and mitigating wellbore instability, and optimizing drilling trajectories in complex lithological and stress regimes. Such analyses prevent costly non-productive time (NPT) and mitigate operational risks, especially in deepwater, high pressure / high temperature (HPHT), and structurally complex settings.

Beyond well integrity, reservoir geomechanics plays a pivotal role in understanding and managing fault and fracture reactivation, including the prediction of natural fracture networks and their impact on reservoir performance. Accurately characterizing fracture and fault mechanics is indispensable for safe depletion strategies, waterflood management, and carbon capture and storage (CCS) projects, in which containment assurance hinges on precise fault stability assessments. In hydraulic stimulation design, geomechanics guides fracture orientation, propagation control, and treatment optimization, ensuring effective reservoir contact while minimizing risks of out-of-zone growth or induced seismicity.

The global application of these methods, spanning from carbonate and clastic reservoirs, onshore and offshore environments, to conventional and unconventional developments, has proven their strategic value. Projects in the Middle East, South America, North Africa, North America, and Asia have demonstrated that integrating geomechanics into field development planning unlocks substantial gains in recovery efficiency, operational safety, and cost control.

As the energy sector transitions towards a more diverse portfolio including geothermal energy, hydrogen storage, and large-scale CCS, reservoir geomechanics assumes an even greater strategic importance. The same analytical rigor used in oil and gas ensures the mechanical integrity of subsurface assets in these emerging domains, safeguarding both environmental and economic outcomes. Geomechanics is a core discipline enabling responsible and high-performance subsurface engineering worldwide.

2 METHODOLOGY

2.1 *The finite element method in numerical simulations*

Finite Element Method (FEM) modelling has become a fundamental tool in reservoir geomechanics, enabling the quantitative simulation of coupled stress, strain, and pore pressure evolution in complex geological settings. This numerical framework allows the integration of heterogeneous material properties, complex boundary conditions, and non-linear constitutive laws, thereby supporting robust predictions in drilling, completion, production, and stimulation operations.

The governing equations (Biot, 1941; Dean et al, 2001; Settari and Walters, 2001; Zienkiewicz et al., 2005; Zoback, 2010) for numerical fluid-flow coupled, geomechanical simulations are based on a deformable porous continuum (the rock) with one or more mobile fluid phases under quasi-static conditions. The mechanical equilibrium in a porous reservoir is described by the quasi-static form of the linear momentum balance:

$$\nabla \cdot \sigma + b = 0 \quad (1)$$

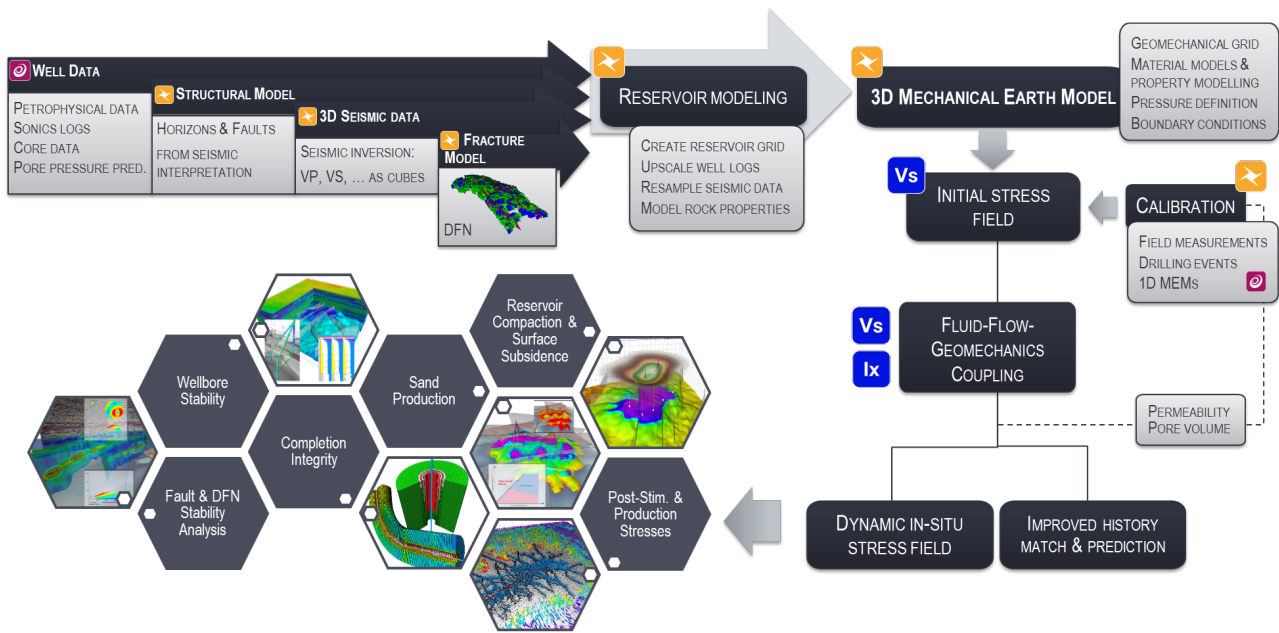


Figure 1: Overview of a 3D coupled geomechanical modelling workflow (modified after Haas et al., 2023).

Where:

σ – total stress tensor [Pa]

b – body force vector (e.g., gravity) [N/m³]

In poro-mechanics, the effective stress principle (Biot, 1941) relates total and effective stresses as:

$$\sigma = \sigma' - \alpha p I \quad (2)$$

Where:

α – Biot's coefficient [–]

p – pore pressure [Pa]

I – identity tensor [–]

Fluid mass conservation is expressed as:

$$\partial/\partial t (\alpha \nabla \cdot u + M p) - \nabla \cdot (\mu/k \nabla p) = q \quad (3)$$

Where:

u – displacement vector [m]

M – Biot's modulus [Pa]

k – permeability tensor [m²]

μ – fluid viscosity [Pa·s]

q – volumetric source/sink term [m³/s]

In FEM, the domain is discretized into elements, and the displacement field u is approximated by:

$$u(x) = \sum_{i=1}^n N_i(x) u_i \quad (4)$$

Where:

$N_i(x)$ – shape function of node i [–]

u_i – nodal displacement vector [m]

n – number of nodes per element [–]

Coupled flow–geomechanics problems are solved by integrating the above with the discretized mass balance equation, producing a fully coupled system that captures both mechanical deformation and fluid flow.

2.2 The Mechanical Earth Model (MEM) workflow applied for new energy and oil/gas projects

The finite element simulations are commonly embedded within a comprehensive 3D reservoir geomechanics workflow (Herwanger and Koutsabeloulis, 2011), called a mechanical earth model (MEM), which integrates geological, geophysical, petrophysical, and engineering data (Plumb, 1994) into a coupled flow–geomechanics framework. This 3D workflow is designed to address multiple operational objectives, including near-wellbore stability, fault and fracture reactivation risk assessment, hydraulic stimulation optimization, reservoir compaction forecasting, carbon capture and storage (CCS) containment assurance, to just name a few examples.

The workflow follows a structured sequence:

1. Data Acquisition and Geomechanical Model Construction
 - Structural interpretation from seismic data to define faults, horizons, and fracture corridors.
 - Petrophysical evaluation to populate 3D property grids of porosity, permeability, elastic moduli, and strength parameters.
 - In-situ stress and pore pressure characterization from well logs, leak-off tests (LOT), and mini-frac data.
2. Mechanical Earth Model (MEM) assembly
 - Construction of a calibrated 3D static geomechanical model using FEM mesh generation that honours reservoir and overburden geometries.
 - Assignment of mechanical properties, anisotropy, and failure parameters (Mohr–Coulomb, Hoek–Brown, Drucker–Prager, or viscoelastic rheology).
3. Coupled Flow–Geomechanics Simulation
 - Implementation of Biot's poro-elasticity theory to capture stress–pressure coupling.

- Integration with reservoir simulation outputs (production/injection schedules, pressure changes) to update stress-strain fields over time.
4. Application-Specific Analysis
- Wellbore Stability: Determination of minimum and maximum allowable mud weights, breakout and collapse pressures, and sanding potential.
 - Fault Stability Analysis: Slip tendency and dilation tendency mapping to quantify reactivation risks under depletion or injection.
 - Hydraulic Stimulation: 3D fracture growth simulations, interaction with natural fracture networks, and stage optimization.
 - Reservoir Compaction/Subsidence: Time-lapse deformation prediction, including surface subsidence and wellbore strain forecasts.
 - CCS and New Energy Applications: Long-term fault sealing capacity assessment and fracture containment studies under CO₂ injection pressures.
5. Calibration and Validation
- Model calibration against observed drilling events, micro-seismicity, production-induced subsidence, and time-lapse seismic (4D) deformation fields.
 - Sensitivity analysis on key parameters (Biot's coefficient, friction angle, cohesion) to constrain uncertainty.

3 RESULTS AND DISCUSSION

The generated results based on these workflows are interpreted across a vast set of applications.

3.1 Near-Wellbore Stability

Finite element simulations of the near-wellbore stress field (Figure 2) reveals distinct zones of compressive breakout and tensile fracturing, depending on mud weight and in-situ stress orientation. In high-angle wells drilled in anisotropic stress regimes, breakout initiation occurred at azimuths aligned with the minimum horizontal stress, consistent with Mohr-Coulomb failure predictions. The analysis provided optimized mud weight windows, reducing the risk of costly stuck pipe and wellbore collapse events. This is especially critical in HPHT fields where narrow drilling margins demand precise control of mud density.

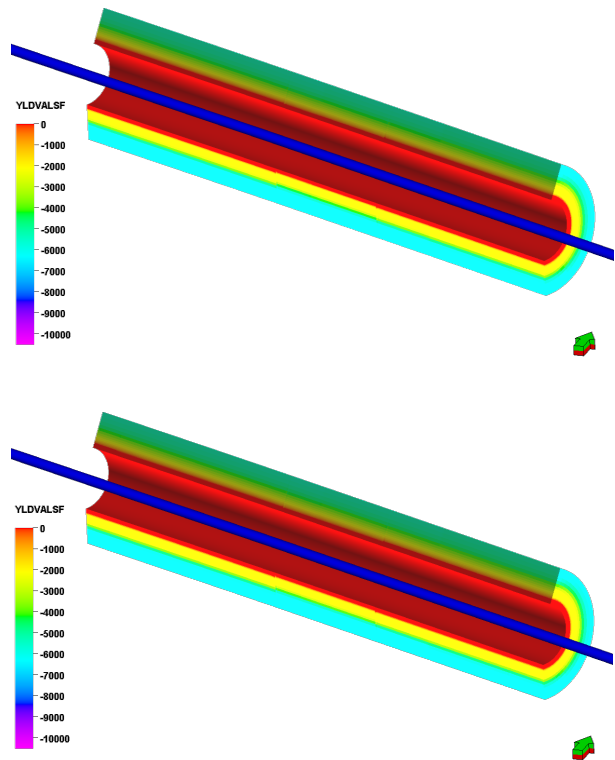
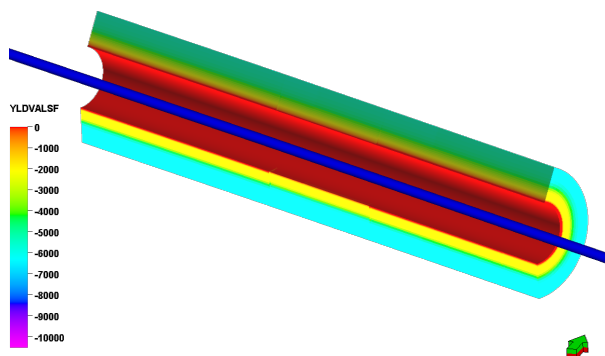


Figure 2: Breakout geometry for different mud weights (top: 6.5 ppg, middle: 4.4 ppg, bottom: 4.2 ppg) based on near wellbore geomechanics modelling results showing rock yield value failing in shear.

3.1.1 Fault and Fracture Reactivation

3D slip tendency maps generated from coupled flow-geomechanics FEM simulations identified critically stressed fault segments under production-induced pressure drawdown. Reactivation risk was highest in faults intersecting high-permeability channels where pore pressure depletion propagated rapidly. Shear failure tendency increased by more than 25% in some fault planes, highlighting the potential for induced seismicity or unwanted fluid migration.

3.1.2 Hydraulic Stimulation Design

Fracture propagation modelling (Figure 3) showed that in layered formations with strong mechanical contrasts, fractures tended to divert into weaker strata, risking out-of-zone growth. When natural fracture networks were included in the simulation, fluid diversion into secondary fractures enhanced stimulated reservoir volume (SRV) but increased leak-off losses. Optimizing treatment stages and pump schedules based on geomechanical predictions improved stimulation efficiency by 15-20% in field trials.

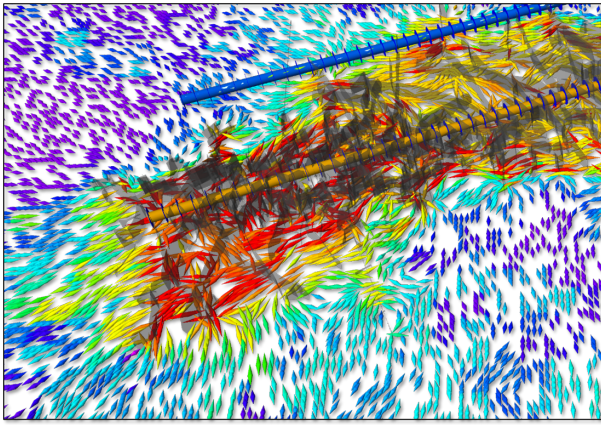


Figure 3: In-situ horizontal stress changes during hydraulic fracturing.

3.1.3 Reservoir Compaction and Subsidence

Field-scale coupled models predicted up to 1.2 m of surface subsidence in high-depletion gas reservoirs over a 15-year period, consistent with satellite InSAR measurements. Compaction-induced casing deformation was also observed in deviated wells intersecting high-porosity zones, with FEM simulations correctly predicting the location and magnitude of strain.

3.1.4 CCS Containment Assurance

In CO₂ injection scenarios (Figure 4), geomechanical modelling demonstrated that pore pressure increases could approach critical slip thresholds in sealing faults if injection rates exceeded designed limits. However, optimized injection schemes kept faults in a stable regime while maintaining containment integrity. Over a 50-year simulation, the FEM-predicted stress evolution confirmed no risk of fracture opening above the caprock seal.

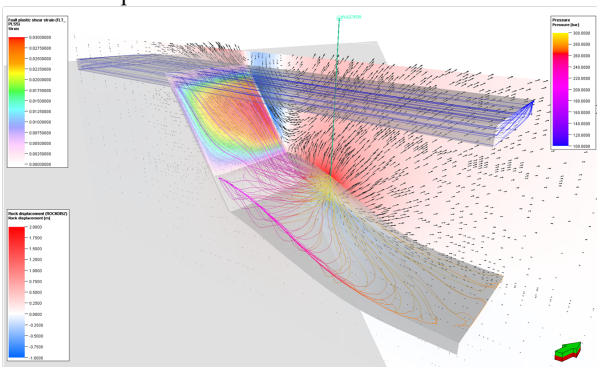


Figure 4: Fault leakage paths for CCS integrity assessment.

These applications demonstrate that when geomechanics is tightly integrated into field planning, FEM simulations enable quantifiable risk reduction and performance optimization across the asset lifecycle. Whether applied to drilling, stimulation, production management, or storage operations, the approach delivers clear operational and economic value, from deepwater oilfields to unconventional shale plays and from mature depletion projects to next-generation CCS initiatives.

4 CONCLUSIONS

This article demonstrates the critical role of finite element-based reservoir geomechanics in predicting and managing the mechanical behaviour of subsurface systems under production,

injection, and stimulation operations in the oil and gas industry, with direct applicability to emerging energy transition projects.

1. Finite Element Modelling (FEM) provides a rigorous framework for simulating coupled poroelastic and elastoplastic responses of reservoirs, enabling quantitative prediction of geomechanical risks and operational limits.
2. Near-wellbore stability analysis reduces uncertainty in safe mud weight estimation and mitigates wellbore failure risks, particularly in HPHT, deepwater, and depleted reservoirs with narrow drilling margins.
3. Fault and fracture reactivation assessments via slip/dilation tendency mapping are essential for optimizing injection and depletion strategies, reducing the probability of induced seismicity and containment loss.
4. Hydraulic stimulation modelling that integrates anisotropic properties and pre-existing fractures increases stimulation efficiency while preventing out-of-zone fracture propagation.
5. Reservoir compaction and subsidence forecasting supports proactive infrastructure protection, well integrity management, and long-term production planning.
6. CCS containment assurance modelling applies proven oil and gas workflows to CO₂ storage, ensuring long-term fault and seal stability in compliance with regulatory requirements.
7. The 3D geomechanical earth model is a central decision-making tool, integrating geological, geophysical, petrophysical, and engineering datasets to deliver calibrated, predictive, physics-based insights.
8. Established oil and gas geomechanics methodologies are directly transferrable to geothermal, hydrogen storage, and CCS, enabling continuity of technical expertise in the energy transition.

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