Stress distribution around complex salt structures:

A new approach using fast 3D boundary element method

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Session 2.17: Salt Tectonics
Session 6.04: Innovative Technologies
Session 2.10: Naturally Fractured Reservoirs – Outcrop and Case Studies
Session 4.05: Geomechanics

Abstract

During the last decade geologists and engineers have used the Finite Element Method (FEM) with elasto-plastic or visco-plastic behavior to simulate salt in order to gain a better understanding of the *in-situ* stress distribution. However, building such FEM models can become time consuming and challenging, especially when complex geometry is involved, and modeling elaborated non-linear salt behavior can take hours to days to process. We have developed a different approach using a fast 3D Boundary Element Method (BEM). Instead of using non-linear mechanical behavior of salt, we use the assumption that salt can be viewed as a pressurized cavity for which unknown parameters such as far field stress and salt pressure gradient are inverted using available data such as observed natural fracture (*e.g.*, joints, faults…) or recorded stress data (*e.g.*, breakout, LOT, micro-seismicity…) associated to past or actual deformation around salt. To verify this approach, BEM results have been validated against known 3D analytical solution for pressurized spherical cavity and compared to published, more complex, 3D FEM salt models. The efficiency of this new approach, in terms of model construction and mechanical simulation, is demonstrated through a natural example of faults associated to salt diapirs in the Gulf of Mexico.

Introduction

Today, one of the principal active topics in oil and gas is the minimization of risk while exploiting reservoirs near or below salt bodies. Although many oil fields are developed along salt bodies, salt diapirs have always been treated cautiously because of their geological complexity and because the presence of salt bodies modifies the in-situ stress field (Dusseault et al. 2004). Therefore, estimation of stress magnitudes and orientations around and within salt domes represents one of the main challenging predrilling steps.

Many geoscientists have already used geomechanical models to improve in-situ stress understanding around and within salt bodies. Fredrich et al. (2003) investigated using the finite element method (FEM) to analyze stress perturbations around axisymmetric salt bodies. Salt was modeled with a viscoelastic behavior and the surrounding sediments with a linear elastic behavior. Koupriantchik et al. (2005) used stress modeling of salt diapirs to predict zones of wellbore instability. Luo et al. (2012) compared the effect salt has on elastic and elastoplastic sediments using FEM. Sanz and Dasari (2010) model salt with a viscoelastic law using FEM. Although these are established methods, model construction and computation remain time consuming and they require specialists.

Here, we describe an innovative approach that models in-situ stress distribution around salt bodies using the boundary element method (BEM). We assume that salt can be viewed as a pressurized cavity for which unknown parameters such as far-field stresses and salt pressure gradient are inverted using available data such as observed fracture orientation or recorded data (e.g., breakout) associated with the deformation around salt. We demonstrate, through a natural example of a real salt structure from the Gulf of Mexico (GoM), that, on one hand, BEM is as capable as FEM for modeling heterogeneous stresses around salt structures, and, on the other hand, it is more efficient in terms of model construction and computation time.

Theory and Method

As for magma chambers (Muller and Pollard 1977) and pressurized wellbores (Zoback 2010), many researchers compare a salt body to a pressurized cavity (Bowers 2007; Sanz and Dasari 2010; Luo et al. 2012), even though the length and time scales differ. Indeed, a viscous material such as salt could be compared to viscous magma and to a fluid in the wellbore. Although the deformation mechanisms are different, the basic mechanics (pressurized cavity) are similar. In our simulations, we used iBem3D (Maerten et al. 2014), a 3D BEM, to compute stress distribution around salt diapirs. With this method, surrounding sediments are modeled using an elastic behavior but salt is not modeled explicitly. Only the salt pressure simulated as normal traction boundary condition along the salt surface (discontinuity) is modeled.

To verify that we can model stresses around salt, we compare iBem3D results with published results using FEM simulations with nonlinear salt behavior. The comparison is done using an example taken from Luo et al. (2012). It describes an FEM simulation of a buried spherical viscoelastic salt surrounded by elastic sediments and subjected to a far-field uniaxial vertical compression (Fig. 1a). The vertical far-field stress σ_v is identified as function of the sediment weight: $\sigma_v = \rho_{\text{sed}} \times g \times z$ and the horizontal stresses are $\sigma_H = \sigma_h = 0.7 \times \sigma_v$. The salt has a diameter of 2 km and it is buried at 4 km depth (top of the salt).

Figure 1c shows the FEM results and how the three principal stresses vary along a vertical well passing through the center of the salt. It is important to note that the isotropic stresses ($\sigma_H = \sigma_h = \sigma_v$) inside the salt have a gradient related to the density of the modeled salt, and it is shifted because of excess or lack of pressure, which we call *salt pressure shift* (SPS). SPS is an unusual parameter that depends on many factors, such as salt body shape, connected or disconnected salt, the far-field stresses, sediment mechanical properties, sediment pore pressure, salt mechanical properties, and salt and sediment behavior.

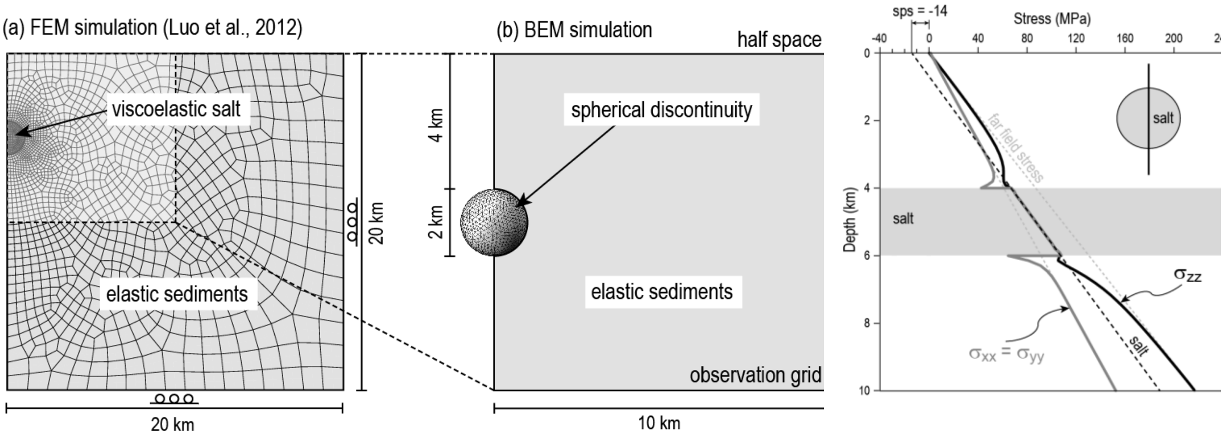

***Figure 1:** Model configuration for (a) FEM model from Luo et al. (2012) and (b) BEM model. (c) Stress results from FEM along a vertical well through the salt.*

Since we are modeling salt behavior using normal traction boundary conditions along the salt surface representing the salt pressure, we need information about the pressure distribution. From the salt density and FEM results, we know the isotropic stress gradient and the SPS (SPS=-14 MPa in Fig. 1c). These parameters, together with the far-field remote stress, are used to constrain the BEM simulation. Figure 2 shows that the vertical stress (σ_v) computed with the two methods compare very well.

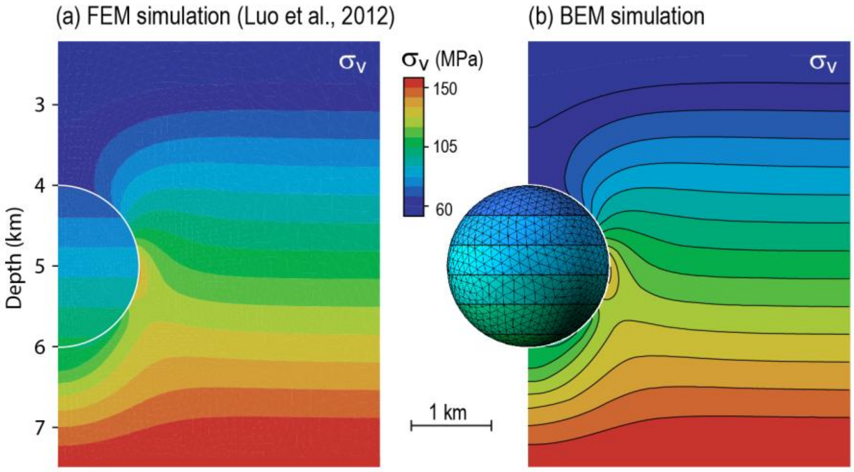

***Figure 2:** Comparison between (a) FEM results from Luo et al. (2012) and (b) iBem3D results. The total vertical stress σ_v is displayed.*

Whereas SPS is a result in FEM simulations, it is an input parameter in BEM simulations when setting pressure boundary conditions along the salt surface. Therefore, one of the main challenges when using BEM for computing stress perturbation around a salt diapir is to estimate the SPS parameter. In our methodology, the SPS and the far-field stresses are either imposed or recovered using the inversion technique developed by Maerten et al. (2016a, 2016b).

Case Study from the GoM

The methodology has been applied in the Eugene Island area in the northern part of the GoM at the edge of of the SE-trending shelf margin into the salt dome minibasin province (Fig. 3). It has an area of 200 km × 100 km. Here, we make the assumption that faults were developed within the perturbed stress field caused by salt diapirs (Fig. 4).

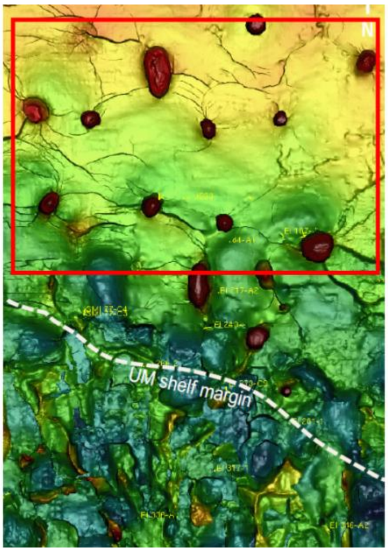

Figure 3: *Location of the study area relative to the edge of the shelf margin (Snyder et al. 2010).*

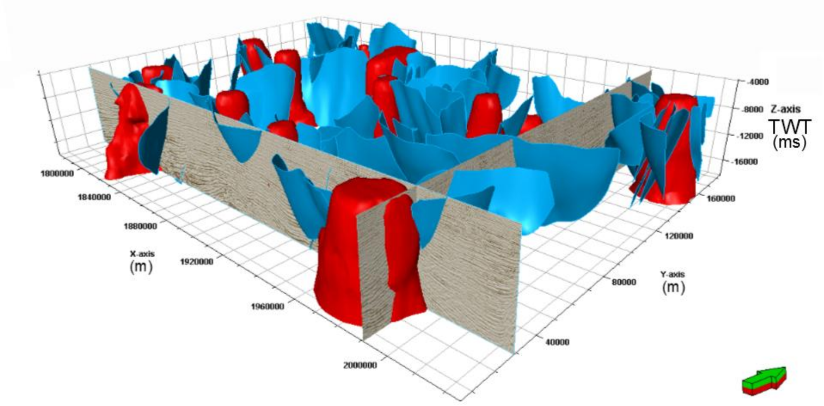

Figure 4: *Interpreted and modeled 93 faults (blue) and 12 salt diapirs (red) from depth-converted 3D seismic reflection data (courtesy of WesternGeco).*

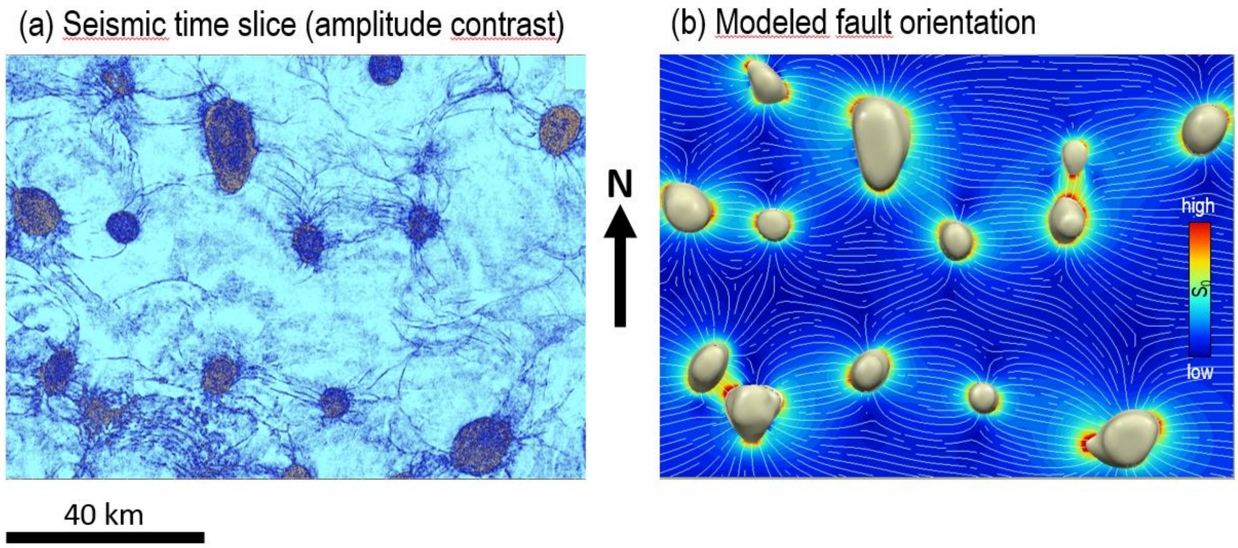

Figure 5: *Comparison between (a) the seismic data (time slice at z=5 km) and (b) the geomechanical simulation results for the GoM. Maximum Coulomb shear stress* (So) *is plotted on the map on the right as well as the orientation of the model shear planes.*

In our simulation, the faults are used to constrain the far-field tectonic stress inversion. Inversion and forward stress simulation took approximately 10 minutes and gave a normal regime, which is coherent with the extensive context in the GoM. Recovered orientation of σ_H is N114°, which follows the orientation of the shelf margin edge (**Erreur ! Source du renvoi introuvable.** 3). Figure 5 shows a good comparison between observed faults from the seismic reflection data (dark blue lines in the amplitude contrast map) and the computed fault orientation (white streamlines). Observed fault concentration (density) compares well to the stress concentration. We used the maximum Coulomb shear stress (S_0), which is an index for fault density. S_0 is the maximum shear stress that would occur on optimally oriented conjugate shear fractures as defined in Jaeger et al. (2007).

Conclusions

We have demonstrated that we can efficiently model heterogeneous stresses around salt using the BEM technique and that the model building effort as well as the computation time can be highly reduced compared to FEM simulations (hours or days of computation). Through a real case study from the GoM, we have shown that inversion technology can be used to recover far-field stress and internal pressure (SPS) necessary to constrain the geomechanical simulations. Even though we used the final geometry of the growing salt structures, we have shown that the computed stresses around complex salt diapir geometry in the GoM nicely correlate with the observed faults that developed around the salt diapirs. Other types of data could be used to model present-day stress field around salt such as measured in-situ stresses.

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