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Research paper

Comparison of evolutionary and static modeling of stresses around a salt diapir

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ABSTRACT

We compare an evolutionary with a static approach for modeling stress and deformation around a salt diapir; we show that the two approaches predict different stress histories and very different strains within adjacent wall rocks. Near the base of a rising salt diapir, significantly higher shear stresses develop when the evolutionary analysis is used. In addition, the static approach is not able to capture the decrease in the hoop stress caused by the circumferential diapir expansion, nor the increase in the horizontal stress caused by the rise of the diapir. Hence, only the evolutionary approach is able to predict a sudden decrease in the fracture gradient and identify areas of borehole instability near salt. Furthermore, the evolutionary model predicts strains an order of magnitude higher than the strains within the static model. More importantly, the evolutionary model shows significant shearing in the horizontal plane as a result of radial shortening accompanied by an almost-equivalent hoop extension. The evolutionary analysis is performed with ELFEN, and the static analysis with ABAQUS. We model the sediments using a poro-elastoplastic model. Overall, our results highlight the ability of forward evolutionary modeling to capture the stress history of mudrocks close to salt diapirs, which is essential for estimating the present strength and anisotropic characteristics of these sediments.

1. Introduction

During the last two decades, understanding the stress, material behavior, and pore pressure around salt bodies has become increasingly important. Many wells have encountered drilling problems near salt, leading to additional expense or even abandonment (Dusseault et al., 2004; Meyer et al., 2005; Willson et al., 2003; Zhang et al., 2008). In addition, new plays have been discovered beneath allochthonous and autochthonous salt, making it necessary to drill through the salt body to reach the target (Adachi et al., 2012; Beltrão et al., 2009; Mackay et al., 2008).

Salt and the evolution of its cross section to the present day geometry has been studied extensively using kinematic restorations (Rowan and Ratliff, 2012). Such studies aim to explain the observed geologic cross section through a sequence of plausible past sections; however, they do not look into stresses within the sediments. Similarly, large-strain numerical studies (Albertz and Beaumont, 2010; Albertz et al., 2010; Allen and Beaumont, 2012; Chemia et al., 2009; Goteti et al., 2012; Gradmann et al., 2009; Schultz-Ela, 2003) have focused on the geologic evolution of salt systems without modeling the geomechanical response of the wall rocks. On the other hand, geomechanical analyses can provide estimates of the stress field and pore pressure around salt; such analyses are necessary in order to design the most economic well path, ensure borehole stability, and minimize the risk of wellbore fracturing and formation fluid influxes.

Most geomechanical studies around salt have used the *static* approach, in which the model is built using the present-day salt geometry and an assumed initial stress field. Most published studies assume idealized salt geometries (Fredrich et al., 2003; Luo et al., 2012a; Nikolinakou et al., 2012; Orlic and Wassing, 2013; Sanz and Dasari, 2010), but a few studies use geometries devised on the basis of seismic information (Henk, 2005; Koupriantchik et al., 2005, 2004; Nikolinakou et al., 2013). The initial stress field usually assumes uniaxial strain deposition (a given horizontal-to-vertical stress ratio), meaning that shear stresses are present within the salt body at the beginning of the analysis. The static analyses are driven by the fact that the salt, being viscous, cannot

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sustain deviatoric stresses, and so it deforms to achieve an isostatic stress state (Schutjens et al., 2010; Urai and Spiers, 2007). Deformation of the salt body places stress loads on neighboring sediments and, as discussed in the studies referenced above, causes stress perturbations, stress rotations, and pore pressure changes. The static analyses are able to capture a significant part of the salt–sediment interaction, and for this reason the energy industry has developed elaborate three-dimensional static geomechanical tools. However, static analyses cannot account for stress or pore-pressure changes that develop as a result of the evolution of the salt geometry to its current shape.

Geomechanical *evolutionary* models, on the other hand, can simulate the development of the salt cross section to its final geometry. Contrary to certain static models (and to restoration studies), this final salt geometry does not match the real present-day geometry observed in seismic sections. However, evolutionary models provide a powerful tool to simulate and understand how stresses re-distribute in the wall rocks near a moving salt.

The major benefits of the evolutionary models are the following:

a) Evolutionary models simulate sedimentation concurrently with the evolution of the salt section. The stresses within the basin develop as a function of both the depositional process and the loading from the salt. The models do not assume that the horizontal stresses develop as a ratio of the vertical during sedimentation (i.e., uniaxial strain deposition (Matthews and Kelly, 1967; Zoback and Healy, 1984)).
b) Evolutionary models simulate the accumulation of strain (resulting from mechanical and/or non-mechanical processes), and hence maintain a memory of the loading history. Such a memory is essential for determining the current strength and deformation characteristics of mudrocks (Terzaghi et al., 1996).

In comparison to static analyses, evolutionary ones require longer preparation and run times and greater computational power. Furthermore, the industry has already invested in static modeling tools. Therefore, investigation and quantification of the improvement in stress predictions achieved by the evolutionary analyses is important. In this article we compare the poro-elastoplastic stress changes around a salt diapir, as predicted by a static analysis performed using ABAQUS (Version 6.9), with the stress changes predicted by an evolutionary analysis performed using ELFEN (Rockfield, 2010). Sanz et al. (2011) made a similar comparison, using the same finite-element tools, but did not include deformations and loading histories. We extend their work and show that the evolutionary approach predicts much higher strains and dissimilar stress histories, with final shear stresses that are different at vital parts of the model.

2. Finite-element models

We compare a static model run within the finite-element program ABAQUS (Version 6.9) with an evolutionary model developed within the finite-element program ELFEN® (Rockfield, 2010). Because of its versatility, robustness, and open interface allowing user-developed material models, ABAQUS™ has been employed extensively within the energy industry for the development of static models. Combining the implicit porous response with the large deformations associated with deposition and salt movement is more challenging. We employ ELFEN® for the evolutionary analyses because it offers a forward modeling technology that is based on a finite strain, quasi-static, explicit, Lagrangian formulation, complemented by automated adaptive remeshing techniques. In addition, ELFEN® can simulate sedimentation and includes computational features developed for the modeling of salt diapirs (Peric and Crook, 2004; Thornton et al., 2011).

2.1. Model set-up

For the evolutionary model that we construct in ELFEN, we use an axisymmetric model to describe a three-dimensional salt diapir (rotation of the cross section shown in Fig. 1, Nikolinakou et al. (2014)). Because the structure is axisymmetric, all horizontal sections are circular. Initially, the salt is 12 km thick at the center of the diapir and 6 km thick beneath the far-field sedimentary basin. The initial sedimentary basin is 6.25 km thick at the far-field boundary ($r = 20$ km, Fig. 1). The top of the salt diapir is buried by 250 m of sediment. There is no slip between the diapir and the basin. The base and side boundaries are rollers (zero-normal-displacement, free-slip boundaries), and the model is wide enough that the side boundary is unaffected by any stress perturbations. The initial stresses in the model are geostatic, with a horizontal-to-vertical effective stress ratio of $K_0 = 0.8$ for the sediments and $K_0 = 1$ for the salt. Pore pressures are assumed to be hydrostatic and do not change during the analysis (drained simulation). We simulate sedimentation by aggrading the top of the model to horizontal horizons in increments of 400 m every 500,000 years. The local thickness of the aggraded layer is determined by the surface topography prior to sedimentation. The volume of salt remains constant throughout the simulation.

We model the salt as a solid viscoplastic material using a reduced form of the Munson and Dawson formulation (1979). This is a constitutive model that provides a unified approach to both creep and plasticity and is formulated such that the salt viscosity is a function of both effective stress and temperature. The density is constant and equal to 2200 kgr/m^3, and the equivalent salt viscosity ranges from 10^{18} to 10^{20} Pa s. Basin sediments are modeled as porous elastoplastic, using the SR3 constitutive model from the Elfen® material library (Rockfield, 2010). This model is based on the principles of Critical State soil mechanics (same family as Modified Cam Clay (Muir Wood, 1990)), but it is characterized by a modified yield surface (Crook et al., 2006). For the purpose of this study, we chose the input parameters such that the calibrated SR3 yield surface is very similar to the Modified Cam Clay one. The density is a function of porosity (Fig. 1), and porosity is constantly updated as a function of the stress changes caused by sedimentation and salt loading. Further discussion about the materials used and the

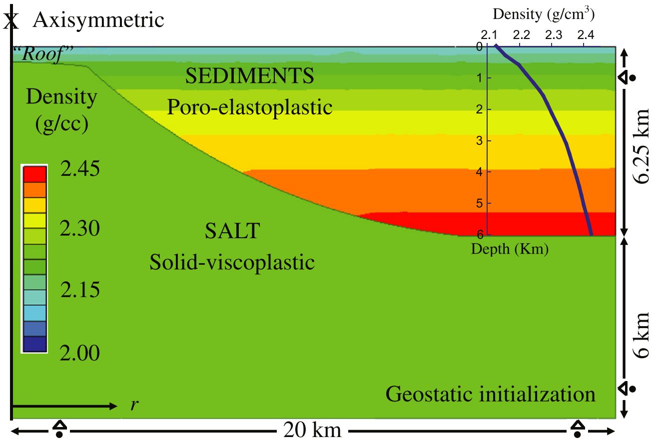

Figure 1. Initial vertical section of evolutionary numerical model prior to sedimentation. Initial diapir = 12 km high at center and basin = 6.25 km deep at edge of model. Contours and inner plot show initial density–depth profile (after Nikolinakou et al., 2014).