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A numerical approach for investigation of stress states induced by salt structures

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ABSTRACT

The main oil and gas reserves around the world are found in regions containing evaporitic rocks. Owing to their low porosity and low permeability these rocks provide favorable conditions for hydrocarbon trapping, increasing the probability of success in oil and gas exploration. Salt rocks exhibit time-dependent strain behavior when submitted to deviatoric stresses. This behavior is described by creep constitutive laws based on deformation mechanics. One of the major challenges in modeling stress states in sedimentary basins in the presence of salt structures is to predict the magnitude of stress perturbations around salt bodies. This work presents a geomechanical approach to take into account the specific weight variation throughout the lithology and the effects of buoyancy in the resulting forces on the interface salt-body/formation. Modeling is driven by the fact that salt bodies cannot sustain deviatoric stresses. Numerical analyses using the Finite Element Method under plane strain conditions provide the results for the comparison of the methodologies found in the literature with the one proposed by the authors. Two synthetic models with salt dome structures are investigated. The proposed approach provided more realistic stress fields in the vicinity of salt structures.

1. Introduction

Salt structures are found in the main oil and gas reserves around the world, such as the Gulf of Mexico, areas offshore of Angola and Nigeria, the North Sea, the Middle East and the Southeast of Brazil. In 2006, a light crude oil reserve has been discovered below a salt layer of 2000 m thickness in Santos Basin, Brazil. The presence of salt structures provides favorable conditions for hydrocarbon trapping, increasing the probability of success in oil and gas exploration. Due to the creep behavior of salt rocks many operational problems during drilling in salt zones have been reported, such as loss of circulation, stuck pipe and casing collapse, leading to well abandon in extreme cases.[1–9] These operational problems are associated to the complex and perturbed stress state induced by salt structures, motivating stability studies of wellbores near and through salt structures.[3–5]

A proper definition of the stress states is relevant also by the determination of well trajectories. The well path and location should be in zones with lower risk of geo-mechanical problems during drilling. This decision depends on information such as leakoff tests (LOT), formation integrity tests (FIT), pressure gradients, in-situ stress state and geomechanical considerations.

Fracture gradients in sedimentary basins with the presence of salt structures are different from those found in other sedimentary basins. For instance, Willson and Fredrich[9] and Baker and Meeks[10] show that the fracture gradient is in order of 5–10% higher than the overburden gradient in salt zones.

Stress perturbations influence the geopressure gradients above and below the salt structure.[2,5,9] Therefore, the prediction of stress perturbations in the formation surrounding salt bodies is important for the identification of zones with risk of geo-mechanical problems, e.g., rubble zones, tectonic instability zones, salt shear zones, major subsalt pressure regression, among others.[8]

Willson and Fredrich[9] described in their work the potential geomechanical risks and potential pore pressure risks during drilling near- and through-salt. The authors emphasize the necessity to account for geomechanical considerations in the definition of well trajectories, operational window and mud weight. Dusseault et al.[11] also describes the risks and uncertainties of drilling in salt zones. The authors discuss the stresses and fault regime above salt domes and the in-situ conditions around salt domes.

Poiate et al.[3] and Costa et al.[12] present a successful methodology for drilling wells through thick layers of salt (∼2000 m) at depths of 6000 m in the Santos Basin, Brazil. The methodology considers the effect of the geomechanical interaction between salt and adjacent

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formation by the evaluation of the stability of wells. This region has presented numerous problems due to the high temperature and high stresses in the salt layers, leading to a high salt deformation rate (0.05/h).[3] Problems during well drilling were associated with the perturbed state of stresses in the formation adjacent to the salt structure and to salt creep behavior.

In the early 90's, Munson[13–16] introduced creep constitutive laws based on deformation mechanism (Dislocation Glide, Dislocation Climb and Undefined Mechanism) to represent the behavior of salt rocks. In this model, according to temperature conditions and deviatoric stress range to which the rock is submitted, the corresponding deformation mechanism is activated.[13–25]

The diapirism driving forces are unbalanced and the upward movement of salt is continued by buoyancy halokinesis,[26] due to the contrast of specific weight (SW) between salt rock and surrounding formation. The SW of sedimentary rocks increases with depth. Salt rocks are an exception. When the thickness of the overburden is large enough, the SW of the formation becomes greater than the SW of the salt and instability occurs. Due to differential loading, the salt flows to low stress zones. According to Jackson and Talbot,[26] this SW inversion occurs at depths of about 1000 m.

In sedimentary basins with the presence of salt structures, the state of stresses in the surrounding formation is highly complex and perturbed in relation to the far-field stress condition. One of the major challenges in modeling stress states in sedimentary basins in the presence of salt structures is to predict the magnitude of stress perturbations in the surrounding formations. In geo-mechanical modeling, two strategies are used to predict this state of stress: evolutionary and static modeling. The evolutionary models simulate the sedimentation process and the development of faults and folds during the evolution of the salt diapiric geometry.[27–36] These models help understand how stresses redistribute in the rocks near a moving salt body.[35,36] However, by complex salt bodies it is difficult to simulate the sedimentation process that leads to the aimed geometry. Furthermore, the simulation implies in high computational costs.

This work adopts the static modeling strategy[36–45] to assess stress states around salt structures, considering a purely passive model. Once the Campus Basin (Brazil) is a divergent/passive margin basin, tectonic loading is irrelevant. This modeling strategy is driven by the fact that salt bodies cannot sustain deviatoric stresses.

Table 1 presents a summary of geo-mechanical simulation methodologies used to predict the stress perturbations in the formation surrounding salt bodies. The methodologies using static modeling consider the formation SW constant, which overestimates or underestimates the initial stress state and buoyancy halokinesis. The methodology presented in this work defines a more realistic initial stress state and buoyancy halokinesis, resulting in a better estimate of the stress state in the vicinity of salt structures. The calculation of the initial stress state considers variable SW in the vertical and horizontal directions. On the other hand, the assessment of buoyancy halokinesis takes into account the SW contrast between salt dome and surrounding formation. Most methodologies of static modeling ignore the pore pressure effect. In their studies, Nikolinakou et al.[35,42,43] adopt a fully coupled pore-mechanical approach, taking into consideration underpressures and overpressures and obtain reliable predictions of pore pressures around salt domes.

The prediction of pore pressures is also a major challenge in regions with the presence of salt, mainly in zones below the salt. However, this effect is neglected here. In this paper, the stress state is calculated considering static hydrostatic pressures.

Results obtained through Finite Element (FE) analysis are used to compare the proposed methodology with results of the literature.

This paper presents in Section 2 the constitutive models to represent the behavior of the salt rock and the surrounding formation. In addition, it discusses the geo-mechanical modeling of stress states in sedimentary basins in the presence of salt structures. Section 3 presents a finite element model of a synthetic lithology including a salt dome. The calculation of the initial stress states and buoyancy halokinesis using the standard methodology and the one proposed by the authors is illustrated in Sections 4 and 5, respectively. Finally, Section 6 brings the comparison and discussion between the methodologies.

2. Geo-mechanical modeling

In this paper, the creep behavior of the salt body follows the Double-Mechanism-Deformation model (Dislocation Glide and Undefined Mechanism), often used to represent the behavior of Brazilian salt rocks.[3,12,18,20,25]

The strain rate due to creep under steady state condition is:

Table 1
Summary of current models for the evaluation of stresses around salt bodies.

Geomechanical modeling	Author	Constitutive Model[a]		Stress	Poro[b]	Specific Weight[c]
		Formation	Salt			
Evolutionary modeling	POLIAKOV *et. al.*, 1993a.	EP	VE	Effective	H	C
	POLIAKOV *et. al.*, 1993b.	EP	VE	Effective	H	V
	POLIAKOV *et. al.*, 1996.	VEP	VE	Effective	H	V
	DIRKZWAGER & DOOLEY, 2008.	EP	VE	Effective	H	C
	SCHULTZ-ELA & WALSH, 2002.	EP	VE	Total	I	–
	SCHULTZ-ELA, 1993.	EP	VE	Total	I	C
	SCHULTZ-ELA, 2003.	EP	VE	Total	H	C/V
	NIKOLINAKOU et. al., 2014a; 2014b.	PEP	VP	Effective	H	V
Static modeling	FREDRICH *et. al.*, 2003; 2007.	E	MMD	Total	I	C
	KOUPRIANTCHICK *et. al.*, 2004.	E	VE	Total	I	C
	KOUPRIANTCHICK *et. al.*, 2005; 2007.	E	VE	Total	I	C
	COSTA *et. al.*, 2005; BORGES, 2008.	EP	DMD	Total	I	C
	SANZ & DASARI, 2010.	EP	HSIL	Total	I	C
	LUO *et. al.*, 2011.	E/EP	VE	Total/ Effective	H	C
	NIKOLINAKOU *et. al.*, 2011a; 2011b.	PE/PEP	VE	Total/ Effective	H/P	C
	NIKOLINAKOU *et. al.*, 2014b.	PEP	VP	Total/ Effective	H/P	C

[a] E = Elastic; EP = Elastoplastic; VE = Viscoelastic; VEP = Visco-Elastoplastic; VP = Visco-Plastic; PE = Poro-elastic; PEP = Poro-Elastoplastic. MMD = Multiple Mechanism Deformation; DMD = Double Mechanism Deformation; PL = Power Law; HSIL = Hyperbolic-Sine Isotropic Law.

[b] H = Hydrostatic pressure; P = Under/overpressure; I = Ignored.

[c] C = Constant; V = Variable.