CILAMCE
PANACM
RIO DE JANEIRO 2021

Sensitivity analysis of viscous properties of salt rocks during oil well drilling

Luiz E. da Silva Filho[1], Catarina N. A. Fernandes[1], Ricardo A. Fernandes[1], William W. M. Lira[1], Felipe L. de Oliveira[2]

[1]*Laboratory of Scientific Computing and Visualization, Technology Center, Federal University of Alagoas*
Av. Lourival Melo Mota s/n, Cidade Universitária, 57072-900, Maceió, Alagoas, Brazil
luiz.elias@lccv.ufal.br, catarina@lccv.ufal.br, ricardoaf@lccv.ufal.br, william@lccv.ufal.br
[2]*Petróleo Brasileiro - Rio de Janeiro - Matriz, CENPES/PDIDP/EPOCOS/PERF*
Av. Horácio de Macedo, 950, Cidade Universitária, 21941-915, Rio de Janeiro, Brazil
flimao@petrobras.com.br

Abstract. This paper presents a sensitivity analysis of viscous properties of salt rocks during well drilling used to explore and produce oil and gas. The definition of viscous properties of salt rocks is based on triaxial tests performed on samples extracted in-situ. These properties can be difficult to characterize since demand obtaining core samples and performing laboratory tests. In practical terms, the estimated properties of some pre-salt fields are commonly extrapolated to others. However, this generalization can generate elevated errors in several cases. An alternative is to use information about other oil wells already drilled in the same region with similar or equivalent formations to predict anomalous behavior events. In this context, it is studied in this work the mechanical behavior of oil wells drilled through salt rocks according to the variability of its constitutive parameters. The adopted methodology includes: a) data collection on viscous properties of Brazilian salt rocks; b) simulations of oil wells drilled on salt rocks varying the viscous properties of the surrounding formation; and c) calculation of the sensitivity of the variables related to well borehole radial displacement, aiming the better understanding of the relationship between the constitutive properties of the salt rocks and the global mechanical behavior. This study can be used as a startup reference for a retro-analysis to calibrate salt rock constitutive parameters from anomalous behavior events in correlated oil wells. The main contribution of this work is associated to fitting a regression model to events in correlated oil wells using a set of simulation results from the range of the constitutive parameters.

Keywords: Oil wells, viscous properties of salt rocks, sensitivity analysis

1 Introduction

In recent decades, cutting edge technologies have been developed aiming to optimize the oil and gas production processes, mainly to overcome adverse situations imposed by the operating conditions on the fields to be explored. In Brazil's offshore basins, e.g., hydrocarbon reservoirs under thick salt formations bring challenges to drill and maintain producing oil wells.

One of the main problems associated to presence of salt lithology is the creep behavior of these rocks, which produces displacement of the well walls towards its closure. This closure can cause the drill to be trapped during drilling or could compromise the well structural integrity in the production phase. In this context, the creep phenomenon is important and needs to be accurately considered in the oil wells drilled in salt rocks.

On the other hand, the obtainment of the viscous properties used in predicting well closure is complex and expensive. Thus, studies on the sensitivity of these variables are justified, as they can help understanding the errors made when approximate properties are considered. In addition, it is possible to infer the viscous variables that are critical in determining the radial displacement of the borehole.

In this context, this work presents a sensitivity analysis of the viscous properties of Brazilian salt rocks that undergo higher creep strain magnitude, aiming to contribute to a better understanding of the problem. Furthermore, it is expected that this study can be used as a startup estimate for a retro-analysis aiming at calibrating the constitutive parameters of the salt rocks from anomalous behavior observed in situ in correlated oil wells.

2 Methodology

To achieve the proposed objectives, the methodology adopted in the development of this work is based on three main steps, presented in Figure 1.

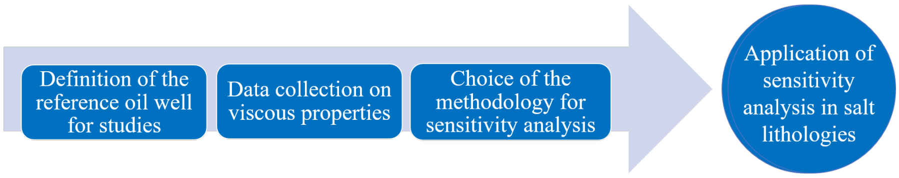


Figure 1. Methodology adopted

In the first stage, a scenario of an oil well that crosses salt formations is chosen and it is used as a reference for the study. The second stage refers to collection of data on the most creep susceptible Brazilian salt rocks which, according to Firme [1], are tachyhydrite, carnallite and halite, mainly in relation to the variability of their viscous properties. Lastly, the sensitivity analysis method is defined and after its applied. These steps are detailed below.

2.1 Reference oil well

The chosen scenario is presented by Costa et al. [2], due to the good detailing of the data needed to reproduce the well. Three scenarios are considered in the study, keeping the original characteristics of the oil well presented by Costa et al. [2]. However, the arrangement of layers is changed in function of the studied rock. The oil wells used are shown in Figure 2.

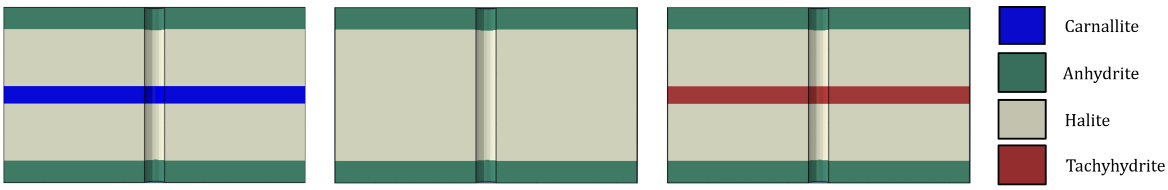


Figure 2. Schematic representation of the reference oil wells

The evaluation of mechanical behavior of oil wells is performed using a computational tool developed in-house, which implements the finite element method using the formulation presented by Araújo [3]. To describe the viscoelastic behavior of Brazilian salt rocks, this software uses the double mechanism (DM) equation, which is used by several authors, which produces good results for Brazilian salt rock behavior (Borges [4] and Poiate [5]). In this double mechanism law, the parameters that define the viscous behavior of each salt rock are the reference creep strain rate $\dot{\varepsilon}_0$, the reference effective stress σ_0 and the stress exponents n_1 and n_2.

2.2 Data on the viscous properties of Brazilian salt rocks

Triaxial tests results on the 3 most common Brazilian salt lithologies are obtained in the literature (Poiate [5], Silva [6], Poiate et al. [7]), data on the variability of the viscous parameters are obtained. In Table 1, the maximum (Max), minimum (Min) and average (Ave) values found for each viscous property of each salt rock are presented. In this table, σ_0 is given in MPa, $\dot{\varepsilon}_0$ is given in hour^{-1}. These data, as seen, are quite dispersed.

Table 1. Data on the vicious properties of Brazilian salt rocks

	Halite				Carnallite				Tachyhydrite			
Value	σ_0	$\dot{\varepsilon}_0$	n_1	n_2	σ_0	$\dot{\varepsilon}_0$	n_1	n_2	σ_0	$\dot{\varepsilon}_0$	n_1	n_2
Min	9.91	4.91e-07	3.00	5.80	5.71	8.22e-07	2.00	3.70	7.02	2.51e-05	2.40	3.00
Max	12.00	1.88e-06	3.36	7.55	10.00	1.55e-04	3.00	7.17	10.00	2.99e-04	3.00	7.49
Ave	10.95	1.18e-06	3.18	6.67	7.85	7.87e-05	2.50	5.43	8.51	1.62e-04	2.70	5.24

2.3 Methodology for sensitivity analysis

According to Saltelli et al. [8], the sensitivity analysis is a tool to evaluate the varying of model responses to input data. The sensitivity analysis adopted in this work is based on measuring the rate of change in the direction of each variable. Thus, using a set of drilling scenarios that are previously simulated, the response surfaces are fitted for each salt rock, using the methodology presented by Santos et al. [9]. These surfaces fit the maximum radial displacement of the oil well as a function of the viscous properties. Using each fitted function $f(\vec{X})$, evaluated on a point $\vec{X}_0$:

$$\frac{f(\vec{X}_0)}{\nabla f(\vec{X}_0)} = \vec{\alpha}. \tag{1}$$

The sensitivity of variable i at point $\vec{X}_0$ is defined as:

$$I_i = (\vec{\alpha}_i)^2 \cdot 100\%. \tag{2}$$

Note that the sensitivities I_i are the squares of the coordinates of a unit vector and, therefore, the sum of these sensitivities is 1 (100%). At each point, the importance is divided among the variables so that the sum of these portions corresponds to 100%, that is, the total sensitivity.

When processing the data, the sensitivities for the viscous parameters of each salt rock are calculated at the points from the database of the respective response surface. For each variable, there is a set of 81 sensitivities, that are obtained from combination of values presented in Table 1 for each rock. The interpretation of the sensitivities obtained is based on theory of elementary effects presented by Morris [10], where the sensitivities of variable $i = 1, \ldots, n$, are associated to two parameters: the mean (μ_i) and the standard deviation (σ_i) of the sensitivities.

The comparison between the sensitivity means allows identifying the factors that have the greatest influence on the model's response, with the highest value, meaning the most influential. The factors with the largest standard deviations are the ones that interact most with others.

3 Results

This section presents the results obtained for the sensitivities of the viscous variables of each salt rock, including the sensitivity factors (μ and σ) and the maximum and minimum sensitivities. Furthermore, violin plots are used, seeking to observe the behavior of the sensitivities for each variable. This chart presents some metrics, such as the maximum, minimum and average values, and it allows to observe how the data are distributed along this range, making it possible to qualitatively infer where the data are concentrated.

3.1 Sensitivities for the reference stress σ_0 and reference creep strain rate $\dot{\varepsilon}_0$

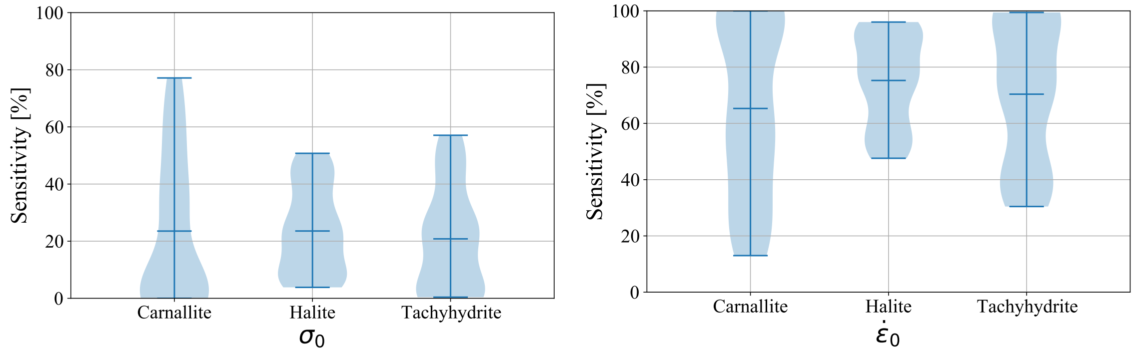
The results obtained for the reference stress σ_0 and reference creep strain rate $\dot{\varepsilon}_0$ are shown in Table 2.

Table 2. Results for the reference stress σ_0 and reference creep strain rate $\dot{\varepsilon}_0$

	Reference stress σ_0				Reference creep strain rate $\dot{\varepsilon}_0$			
Salt rock	μ [%]	σ [%]	$I_{\max}$ [%]	$I_{\min}$ [%]	μ [%]	σ [%]	$I_{\max}$ [%]	$I_{\min}$ [%]
Carnallite	23.54	25.91	77.13	2e-4	65.30	31.12	99.99	13.00
Halite	23.56	15.33	50.76	3.84	75.25	16.23	96.01	47.60
Tachyhydrite	20.81	18.57	57.08	0.40	70.38	25.23	99.42	30.45

In the Table 2, it is observed that the sensitivity of the reference stress is around 20%. It is also observed that the creep strain rate is the most important variable. The average sensitivity ranged between 65 and 75%, however, for all salt rocks, it reached values upper 96%. Figure 3 presents the violin plots for these variables.

Figure 3. Violins plot for the reference stress and reference creep strain rate



(a) Reference stress (b) Reference creep strain rate

Figure 3(a) shows that, even with a wide interval (as seen in the standard deviations of the Table 2), the lower ranges are wider than the upper ones, i.e., the sensitivities of σ_0 are mainly concentrated in values around and below the average. Figure 3(b) shows that, even though the sensitivities range in a considerably for all salt rocks, it is evident that the upper ranges are wider than the lower ranges, i.e., the associated sensitivities are predominantly concentrated in values upper the average.

3.2 Sensitivities for the stress exponents n_1 and n_2

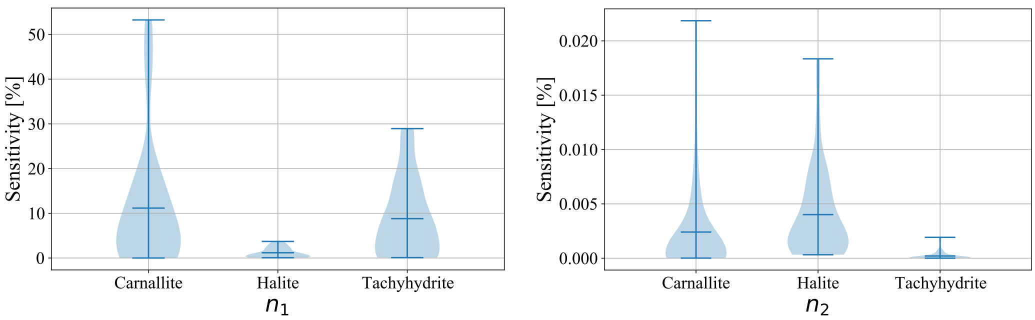
For the stress exponents n_1 and n_2, the sensitivity results are shown in Table 3.

Table 3. Results for the stress exponents n_1 and n_2

	Stress exponent n_1				Stress exponent n_2			
Salt rock	μ [%]	σ [%]	I_{max} [%]	I_{min} [%]	μ [%]	σ [%]	I_{max} [%]	I_{min} [%]
Carnallite	11.16	14.30	53.24	2e-8	2.4e-3	4.5e-3	2.2e-2	4.1e-7
Halite	1.18	1.11	3.71	0.07	4.0e-3	4.1e-3	1.8e-2	3.2e-7
Tachyhydrite	8.81	8.77	28.94	0.09	1.9e-4	4.3e-4	1.9e-3	8.6e-8

These results show that the stress exponents have lower sensitivities than the other viscous parameters ($\dot{\varepsilon}_0$ and σ_0). The standard deviation of the halite sensitivities in the stress exponent n_1 is highlight, because it is considerably smaller than the same parameter for the other salt rocks. Furthermore, the average sensitivities of the stress exponent n_2 are very small. This low influence can be justified because the stress on the observed layer might not have reached the reference stress σ_0, so the exponent n_2 would not be used, influencing very little (in some cases not at all) on the wellbore displacement. Figure 4 presents the violin plots for these variables.

Figure 4. Violins plot for the stress exponents



(a) Stress exponent n_1 (b) Stress exponent n_2

Figure 4 illustrates the similarity between the shapes of the curves, even with different amplitudes. The values of the importance of the variables are concentrated in the lower part of the graph, showing that n_1 has a low importance in most cases. The variable n_2 is negligible in this analyzed scenario.

4 Conclusions

This work presented a sensitivity analysis of the constitutive parameters of Brazilian salt rocks in the evaluation of the mechanical behavior of oil wells. This made it possible to infer the variables that should be closely observed when extrapolated, since those with high sensitivity can introduce large deviations between predicted and observed displacements.

The analysis performed allowed to observe that, for the scenario and values considered, the most sensitive variables in the maximum displacement of the borehole are the reference creep strain rate ($\dot{\varepsilon}_0$) and the reference effective stress (σ_0). On the other hand, the second stress exponent (n_2) is negligible and has no influence. However, statement should be treated with caution, since this result is probably due to the fact that the effective stress acting on the observed layer may not have reached the reference stress σ_0. In this case, the n_2 exponent would not be used or would only be used in deeper layers and, thus, being very little influential on the observed displacement. Thus, even though it is not an absolute statement, it indicates that depending on the scenario, observing the effective stress in the layer under study can help to understand the importance that should be given to the variable n_2.

Another important point to be highlighted is that this work describes a methodology for sensitivity analysis, which can be expanded to future studies from more complex models or even in different areas, because it does not apply only to oil wells.

Acknowledgements. The authors would like to thank PETROBRAS for the financial support related to the development of the research project "Desenvolvimento de ferramentas computacionais para modelagem em tempo real da integridade de estrutura de poço" registered under the legal instrument number 4600588015.

Authorship statement. The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work, and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors, or has the permission of the owners to be included here.

References

[1] P. A. L. P. Firme. Modelagem constitutiva e análise probabilística aplicadas a poços em zonas de sal. Master's thesis, Pontifícia Universidade Católica do Rio de Janeiro, Curso de Pós-Graduação em Engenharia Civil, Rio de Janeiro, 2013.

[2] A. Costa, E. Poiate, C. Amaral, C. Gonçalves, J. Falcão, and A. Pereira. Geomechanics applied to the well design through salt layers in brazil: a history of success. In *44th US Rock Mechanics Symposium and 5th US-Canada Rock Mechanics Symposium*. OnePetro, 2010.

[3] C. Araújo. Desenvolvimento de um elemento finito para modelagem do comportamento de poços verticais em rochas salinas. Master's thesis, Universidade Federal de Alagoas, Centro de tecnologia, Programa de Pós-Graduação em Engenharia Civil, Maceió, 2012.

[4] R. G. Borges. Avaliação numérica de perturbações de tensões associadas a estruturas salíferas e suas influências na estabilidade de poços. Master's thesis, Universidade Federal do Rio de Janeiro, UFRJ, Rio de Janeiro, 2008.

[5] E. Poiate. *Mecânica das rochas e mecânica computacional para projeto de poços de petróleo em zonas de sal*. PhD thesis, Pontifícia Universidade Católica do Rio de Janeiro, Rio de Janeiro, RJ, Brasil, 2012.

[6] I. Silva. *Análise de estabilidade e deformação de cavidades em evaporitos pelo método dos elementos finitos*. PhD thesis, Universidade Federal de Pernambuco. CTG. Programa de Pós-Graduação em Engenharia Civil, Recife, Pernambuco, Brasil, 2015.

[7] E. Poiate, A. Costa, and J. L. Falcao. Well design for drilling through thick evaporite layers. *Society of Petroleum Engineers*, vol. , 2006.

[8] A. Saltelli, M. Ratto, T. Andres, F. Campolongo, J. Cariboni, D. Gatelli, M. Saisana, and S. Tarantola. *Global sensitivity analysis: the primer*. John Wiley & Sons, 2008.

[9] B. Santos, C. Araujo, R. Fernandes, and W. Lira. A customizable computational strategy for evaluation of engineering problems using multivariable interpolation techniques. In *XXXVIII Ibero-Latin American Congress on Computational Methods in Engineering*, Florianópolis - SC, Brasil, 2017.

[10] M. D. Morris. Factorial sampling plans for preliminary computational experiments. *Technometrics*, vol. 33, n. 2, pp. 161–174, 1991.