Modeling of vertical oil well drilled on salt rocks using equivalent subdomains

Gleide K. M. Lins[1], Ricardo A. Fernandes[1], Catarina N. A. Fernandes[1], Emilio C. C. M. Silva[2], William W. M. Lira[1], Eduardo N. Lages[1]

[1]*Laboratory of Scientific Computing and Visualization, Federal University of Alagoas*
Av. Lourival Melo Mota s/n, Cidade Universitária, CEP: 57072-900, Maceió/AL, Brazil
gleidekarolayne@lccv.ufal.br, ricardoaf@lccv.ufal.br, catarina@lccv.ufal.br, william@lccv.ufal.br, enl@lccv.ufal.br
[2]*CENPES/PDIDP/EPOCOS/PERF*
Av. Horácio Macedo - 950, CEP: 21941-915, Rio de Janeiro/RJ, Brazil
emiliosilva@petrobras.com.br

Abstract. This work proposes an alternative approach based on equivalent subdomains for the numerical modeling of vertical oil well drilling in Brazilian pre-salt. These regions are composed of large salt rock layers, which, under high stress and temperature, present creep behavior when they are drilled. Creep causes progressive and time-dependent strains in the direction of wellbore closure, which it can generate stuck pipe and/or well drilling delay. Thus, it is common to use computational simulations to predict the salt rock behavior over its drilling. In the conventional approach, the full salt layer is numerically mapped into a single finite element mesh and one can evaluate the wellbore closure over time using a full plane axisymmetric analysis (Full2D-model) around the oil well vertical axis. In this work, the proposed methodology subdivides the salt layer (domain) into equivalent and independent horizontal stripes (subdomains) to distribute their analysis into several computational threads (multiprocessing), which drastically reduces the computational cost of the wellbore closure evaluation. For each subdomain, a plane axisymmetric analysis (2D-model) or an even faster one-dimensional axisymmetric analysis (1D-model) for several depth values can be used. The 1D-models are simpler and more efficient since they represent the mechanical behavior of a single independent lithology on a given depth. However, on lithology interfaces, the associated mechanical discontinuity is properly managed only by 2D-models because they aggregate a multi-lithology behavior along a given depth interval. Since 1D-models are faster, first a full1D-model is used to estimate the error in the displacement field on the wellbore. The error is measured based on a reference Full2D-model. Then, given a target admissible error, an adaptive scheme that gradually increases 2D-model subdomains over critical regions is employed. This scheme ensures that the maximum error at the wellbore displacement field is the considered target error and defines an optimized subdomain partition. This proposal aims to use different case study scenarios and observe how optimized subdomain partitions behave, in order to identify partitioning patterns according to the characteristics of the scenario. It is expected that the proposed strategy produces good approximations, allowing faster and more practical simulations aiming to assist oil well design and operational demands.

Keywords: Oil well drilling, Salt rocks, Spatial subdivision

1 Introduction

Under the numerous application possibilities, whether as fuel or electricity, oil solidifies as a fundamental energy source for the world economy [1]. In Brazil, the oil and gas industry is responsible for almost 50% of the national energy matrix [2]. In June 2021, 71.2% of this production came from exploratory wells in pre-salt locations, evidencing the high production potential of these regions [3].

The Brazilian pre-salt fields are located in ultra-deep layers and they are composed of extensive thicknesses of salt rocks. These rocks present a creep behavior that represents a phenomenon characterized by the appearance of progressive strains over time when subjected to constant stresses. Thus, when drilled, these rocks tend to move in the direction of the wellbore closure. Furthermore, depending on the scenario, it is possible to find different types of salt rock lithologies. Some have moderate mobility, such as halite, and others are considered quite movable, such as carnallite and tachyhydrite [4]. In general, these regions with high mobility make to higher creep strains, causing operational problems during the drilling, cementing and casing stages [4].

In order to estimate the behavior of these rocks and, thus, carry out the design planning stage, computational simulations based on the finite element method are used [5]. In the conventional approach, the entire salt layer is numerically mapped into a single finite element mesh and one can evaluate the wellbore closure over time using a full plane axisymmetric analysis around the oil well vertical axis. However, despite this methodology being more efficient than a three-dimensional formulation, a high computational cost is still necessary, due to the large thickness of salt rocks and the necessary refinement level to obtain results consistent with the actual wellbore closure. [4]. Allied to this, there is a need to make these simulations faster to facilitate real-time decision making.

A faster alternative is one-dimensional axisymmetric modeling. By representing only the mechanical behavior of a single independent lithology at a given depth, it becomes more efficient than the conventional methodology. However, on lithology interfaces, the associated mechanical discontinuity is properly managed only by conventional axisymmetric modeling, which aggregates a multi-lithology behavior along a given depth interval. Works such as those by Santos et al. [6] and Lins et al. [4] focused on find methodologies to divide the salt domain into parts of conventional and one-dimensional axisymmetric analysis, which would not compromise the quality of the results and optimize the computational cost. This methodology allows dividing the large salt domain into smaller subdomains that can be simulated simultaneously and independently, further reducing the computational cost.

Thus, the purpose of this work is to evaluate the behavior of spatial subdivisions under different types of scenarios. For each scenario, the study presented by Lins et al. [7] is used as reference to determine optimal partitioning for an admissible relative error. A parameter is determined to assess how the spatial subdivision is developed according to the range in depth (directly related to variations in temperature and geostatic stresses), thickness and lithology of the interleaving layers and allowable error. It is expected to identify partitioning patterns according to the characteristics of the scenario and the allowable error, in order to automate and speedup the identification of optimal partitioning.

2 Methodology

The proposed methodology is based on the following steps: a) preparation of study scenarios; b) definition of admissible errors; c) determination of the optimal spatial subdivisions for each scenario; d) investigation of subdivision patterns according to the characteristics of the scenario. In this last step, the comparison between partitions of several scenarios is performed through the conventional modeling subdomains (2D-model). A parameter d is defined and it is studied how it varies according to the characteristics of the 2D-model. Figure 1 illustrates a scheme of the methodology used.

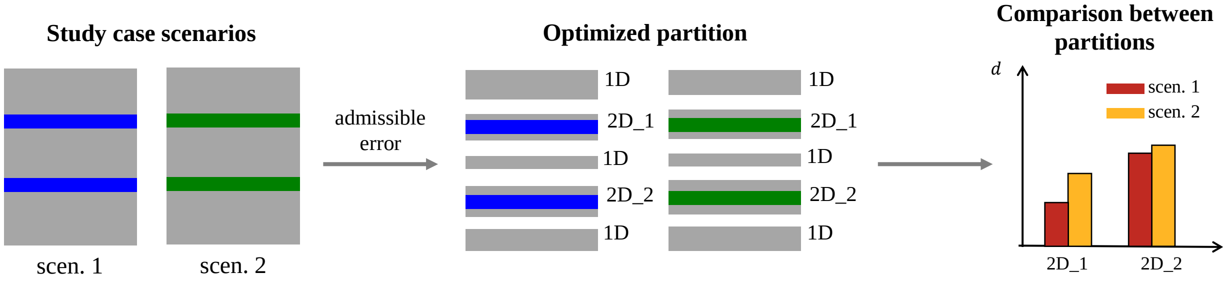


Figure 1. Steps of the proposed methodology

2.1 Case study scenarios

A two thousand meters thick salt layer model composed of two types of lithologies (halite and carnallite or halite and tachyhydrite) is considered. Since the lithologies of carnallite and tachyhydrite generate the highest values of creep strains, they will be called movable lithologies. The regions related to movable lithologies (interleaving layers) are composed of 4 stripes of the same thickness. These thicknesses range from 2 to 5 meters (totalizing 8 scenarios), with the central depth of the interleaving layers remaining constant. For the construction of the scenarios, the intercalations are kept far from each other and from the upper and lower bounds of the domain. The first consideration is made to ensure that, at the end of partition, each plane modeling subdomain contains only one movable lithology. The second consideration is made to avoid that the errors related to use of one-dimensional models at the boundaries interfere in the partition. In this way, the spatial subdivision becomes dependent only on changes between lithologies. Figure 2 presents the default scheme of the scenarios.

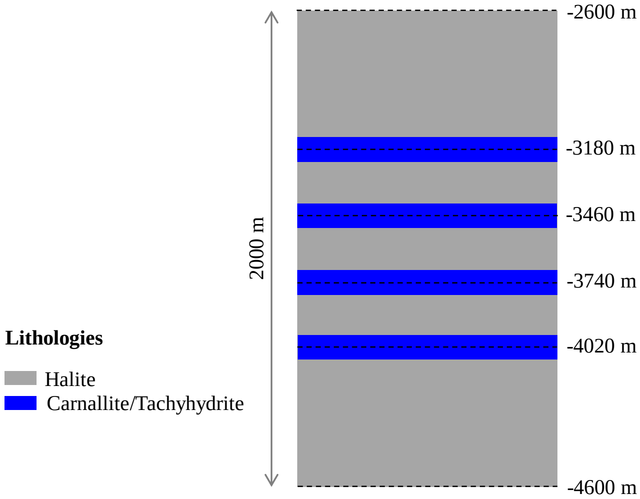


Figure 2. Default scheme for the study case scenario

The properties of the salt rocks used in the study are presented in Poiate et al. [8] and they can be summarized in Table 1.

Table 1. Elastic and viscous parameters of the salt rocks used in the scenario

Parameters	Halite	Carnallite	Tachyhydrite
Young's modulus [GPa]	20.40	4.020	4.920
Poisson's ratio	0.36	0.36	0.33
Density [kg/m^3]	2133	2133	2133
Effective reference stress [MPa]	9.762	5.743	7.865
Reference viscous strain rate [10^{-3} h^{-1}]	0.001671	0.1581	0.1844
Reference temperature [°C]	86	130	86
Stress exponent n1 (double mec.)	3.223	2.868	2.608
Stress exponent n2 (double mec.)	7.562	7.090	7.786

The other model parameters are taken from Costa et al. [9], where the temperature at the top of the salt layer is 40°C and the thermal gradient is 10°C/km. The geostatic stress at the salt top is 39.4 MPa. The salt layer is drilled with a 17.5" diameter, using a mud density of 12 lb/gal. The elapsed computational time is 480 h, considering the entire wellbore already drilled at the initial step.

2.2 Admissible errors

For each of the study case scenarios, three admissible study errors are considered: 5%, 1% and 0.1%. These errors are calculated for the displacements obtained by the end of the simulation and are based on the results obtained by the conventional modeling (plane axisymmetric analysis of the full domain). In this way, the partition is carried out in order to guarantee that the relative error made by the model is smaller than its respective admissible error.

2.3 Optimized partitioning

This step begins with the evaluation of two preliminary models. In the first one, the full domain is numerically modeled using plane axisymmetric analysis. Then, the full domain is modeled again using the one-dimensional axisymmetric formulation. The wellbore closure results obtained by the conventional axisymmetric formulation are used as reference values, and those obtained by the one-dimensional axisymmetric formulation are used to identify the regions where errors are critical, i.e., greater than the allowable error value. In these regions, the conventional formulation is required.

From this preliminary mapping, the initial partition is performed, where the sections with errors greater than the admissible ones are identified as subdomains of conventional modeling (2D-model) and the others as subdomains of one-dimensional modeling (1D-model). The scenario is simulated again with the indicated partition and then it is checked if the 2D-models still makes to inadmissible errors. If any 2D-model continues with an error above the allowed, an increase in its thickness is performed, the partition is updated and then the simulation is carried out again with new error checking. This procedure is repeated until the errors observed for each 2D-model are smaller than the maximum allowable value, so the optimal partitioning is found. Figure 3 summarizes the process of determining the ideal partition. This subdivision methodology imposes that the moving layers are centered in the 2D-model, making the halite thickness above and below the movable lithology the same thickness in the subdomain.

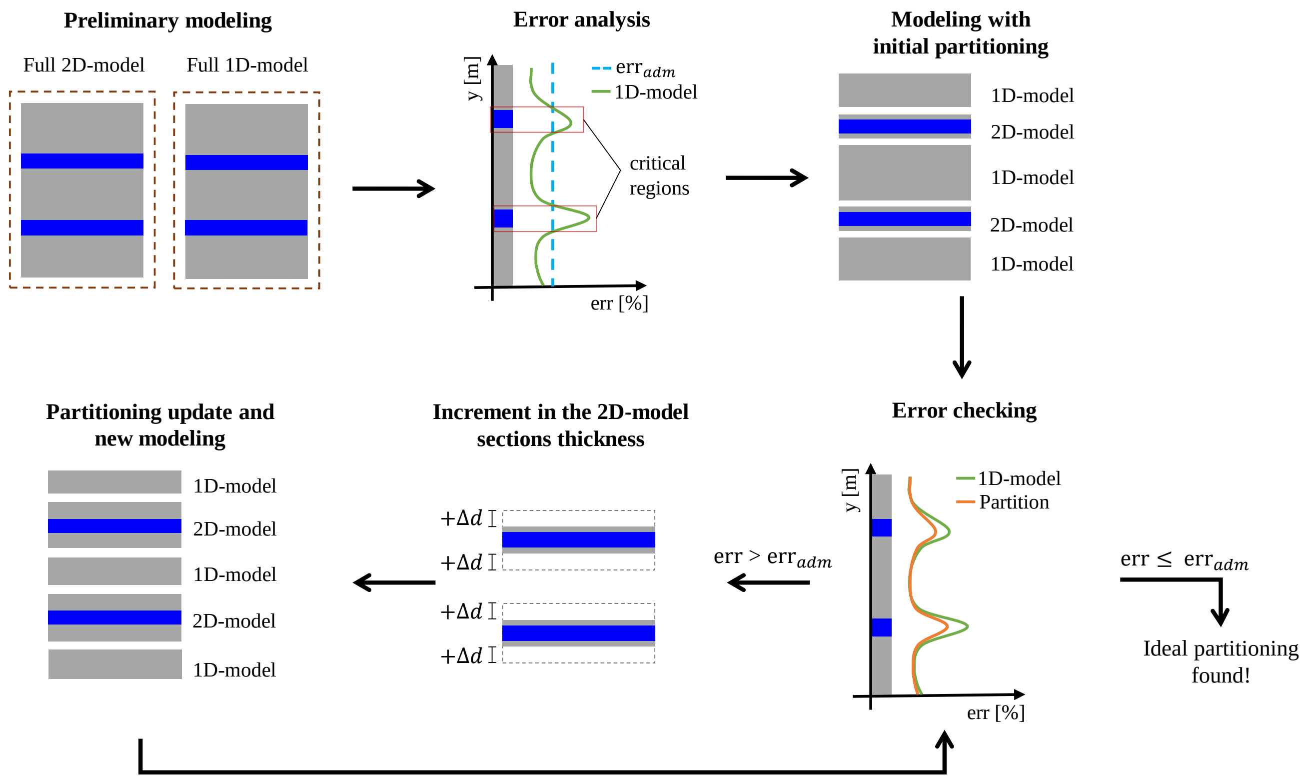


Figure 3. Proposed subdivision methodology

By defining the intervals, an input file corresponding to each 2D-model and one more for all 1D-models is generated. These input files go into the simulator and are modeled independently and simultaneously, using multi-threaded processing. By the end of the simulation, the output files are organized and grouped into a single file with wellbore closure results for the full domain. An *in-house* simulator developed at the Laboratory of Scientific Computing and Visualization (LCCV/UFAL) is used, according to the formulation presented in Araújo [10, 11] and Gonçalves [12]. The viscous behavior of salt rocks is characterized according to the constitutive law of the double strain mechanism [8, 9]. The numerical analyzes were performed on a computer with an Intel Core i7-10510U processor, 2.30 GHz and 8 GB of RAM memory, using the Windows 10 64-bit operating system.

2.4 Comparison between partitions

Based on the imposed considerations on the characteristics of the scenarios and on the determination of the optimal partitioning, for each 2D-model there is a centralized movable layer. This is surrounded by two halite layers with thickness d (see Fig. 4).

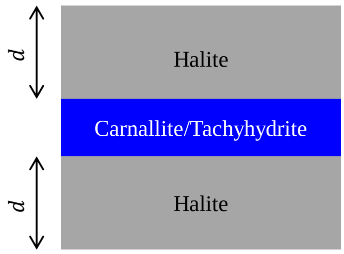


Figure 4. Study scenario structure

Several comparative studies are evaluated in order to investigate how the parameter d varies according to the depth on the 2D-model, admissible error and characteristics of the present interleaving layer (thickness and lithology). The configuration chosen in the scenarios also allows the influence of these parameters to be assessed independently, facilitating the results interpretation.

3 Results and discussions

Tables 2 and 3 present the elapsed computational time for the simulation of the study case scenarios with interleaving layers of carnallite and tachyhydrite, respectively. In all cases, there is a drastic reduction in the computational cost of the models when using the proposed partition strategy.

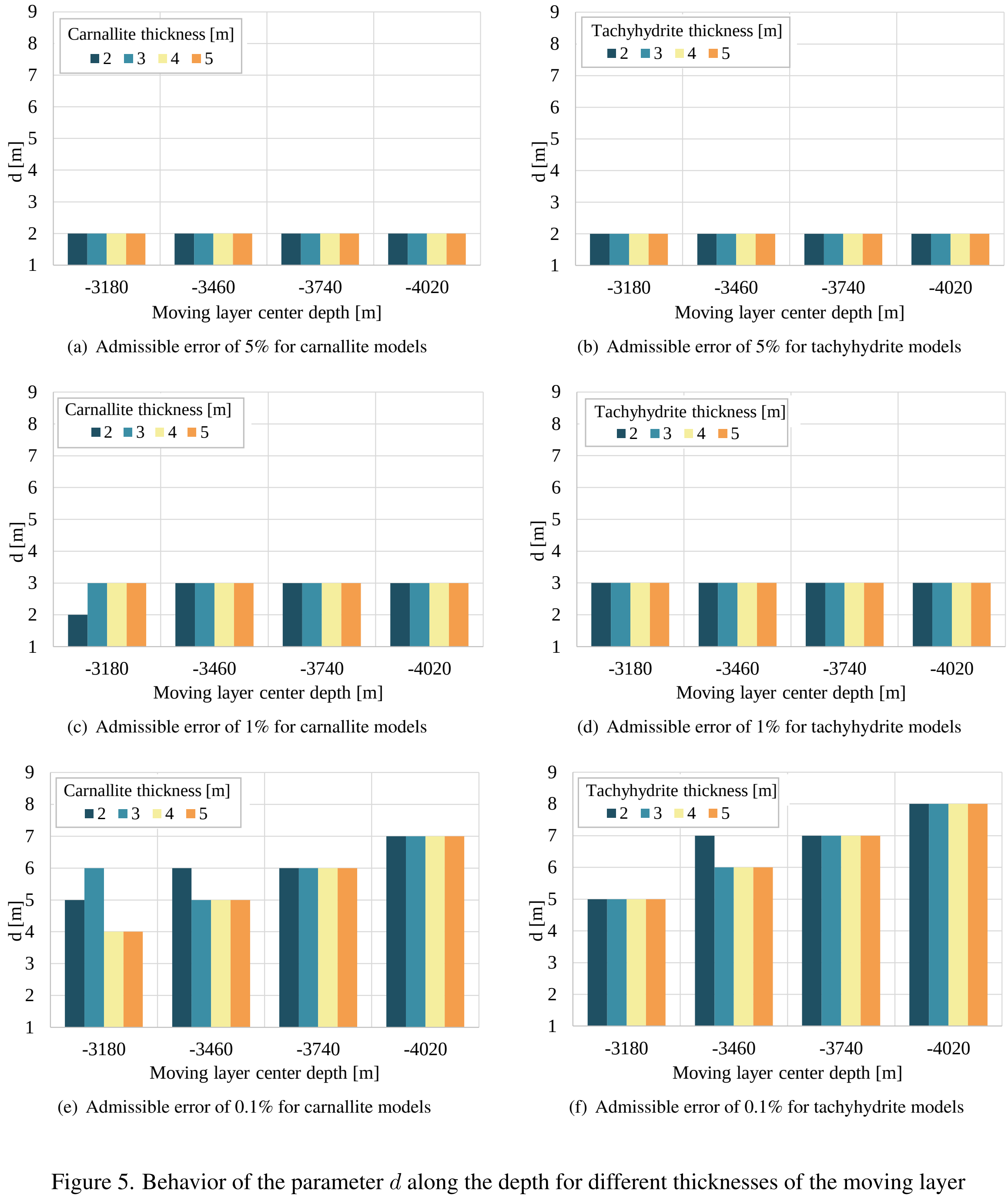
Table 2. Elapsed computational time for carnallite models [in seconds]

Model	Admissible error	Intercalations thickness				Speedup average
		2 m	3 m	4 m	5 m	
Full 2D	-	2652.4 s	2663.7 s	2326.7 s	2916.0 s	-
Partition 5.0%	5.0%	65.7 s	56.8 s	47.6 s	48.3 s	97.9%
Partition 1.0%	1.0%	66.1 s	63.5 s	53.1 s	71.6 s	97.6%
Partition 0.1%	0.1%	67.7 s	66.5 s	57.9 s	145.1 s	96.9%

Table 3. Elapsed computational time for tachyhydrite models [in seconds]

Model	Admissible error	Intercalations thickness				Speedup average
		2 m	3 m	4 m	5 m	
Full 2D	-	4102.8 s	3557.1 s	4484.9 s	4045.0 s	-
Partition 5.0%	5.0%	145.5 s	48.3 s	145.7 s	49.4 s	97.7%
Partition 1.0%	1.0%	145.5 s	50.3 s	148.8 s	75.3 s	97.5%
Partition 0.1%	0.1%	145.4 s	136.6 s	146.5 s	223.3 s	96.0%

Figure 5 illustrates the behavior of the parameter d according to the variation of the moving layer thickness and the increase of the depth for different allowable errors (5%, 1% and 0.1%) and movable lithologies (carnallite and tachyhydrite). In general, it is observed that the thickness d of halite in the 2D-model tends to increase with the reduction of the allowable error. In most cases, the value of d does not depend on the thickness of the movable layer used. Regarding the depth and lithology type parameters, it is noted that they start to affect in d only in the permissible error of 0.1%, implying that for larger errors this influence can be disregarded. Thus, for this error, the thickness d tends to increase as depth increases and mostly with tachyhydrite lithology.



(a) Admissible error of 5% for carnallite models

(b) Admissible error of 5% for tachyhydrite models

(c) Admissible error of 1% for carnallite models

(d) Admissible error of 1% for tachyhydrite models

(e) Admissible error of 0.1% for carnallite models

(f) Admissible error of 0.1% for tachyhydrite models

Figure 5. Behavior of the parameter d along the depth for different thicknesses of the moving layer

4 Conclusions

The results obtained with the optimized partition methodology showed the computational efficiency that the strategy can offer. Eight hypothetical scenarios were evaluated, using admissible errors of 5%, 1% and 0.1% for partition. In all of them, the computational gain exceeded 94%. Furthermore, regarding the behavior of the subdivisions, it was observed that the 2D-model sub-regions tend to increase in thickness with the reduction of the allowable error. The vast majority of results, the variation in the thickness of the interleaving layers (thin sections of carnallite or tachyhydrite) did not interfere with partition. Parameters such as depth (which is directly related to the variation of geostatic stress and temperature along the domain) and type of movable lithology only started to influence the partitioning from the allowable error of 0.1%. In this case, the thickness of the 2D-model subregions increased as depth increases and mostly on tachyhydrite models. The results observed in this work are a startup for defining a domain partitioning methodology according to the scenario to be studied and the permissible error, enabling the obtainment of very fast and accurate closure estimates as shown, accelerating this stage in the project of oil wells in salt.

Acknowledgements. The authors would like to thank PETROBRAS for the financial support related to the development of the research project Computational Models and Tools to Support the Dimensioning of Well Casingsregistered under the legal instrument number 4600549782. The last author acknowledges the support provided by the Brazilian National Council for Scientific and Technological Development – CNPq (grant number 311754/2019-8).

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] A. L. S. Canelas. Evolução da importância econômica da indústria de petróleo e gás natural no Brasil: contribuição a variáveis macroeconômicas. 120 p. Dissertação (Mestrado em Planejamento Energético) – Programa de Pós Graduação de Engenharia, Universidade Federal do Rio de Janeiro, Rio de Janeiro, Brasil, 2007.

[2] BEN. Balanço Energético Nacional (BEN). *Relatório Síntese. 2020 (ano base 2019)*, vol. 1, 2020.

[3] ANP. Boletim mensal da produção de petróleo e gás natural. https://www.gov.br/anp/pt-br/centrais-de-conteudo/publicacoes/boletins-anp/bmp/2021/2021-05-boletim.pdf, 2021.

[4] G. K. M. Lins, R. A. Fernandes, C. N. A. Fernandes, W. W. M. Lira, L. F. M. Almeida, and E. N. Lages. An alternative approach for fast oil well drilling simulations in pre-salt. In *XL Iberian Latin-American Congress on Computational Methods in Engineering - CILAMCE*, Foz do Iguaçu/PR, Brazil. ABMEC, 2020.

[5] R. W. Clough. The finite element method in plane stress analysis. In *Proceedings of 2nd ASCE Conference on Electronic Computation, Pittsburgh Pa., Sept. 8 and 9, 1960*, 1960.

[6] B. L. B. Santos, C. N. Araújo, E. N. Lages, L. F. M. Almeida, J. L. R. Anjos, and E. C. C. M. Silva. Equivalent models of vertical wells closure in saline rocks. In *XL Iberian Latin-American Congress on Computational Methods in Engineering - CILAMCE*, Natal, Brazil. ABMEC, 2019.

[7] G. K. M. Lins, R. A. Fernandes, C. N. A. Fernandes, and W. W. M. Lira. Uma estratégia de subdivisão espacial do domínio para simulações de perfuração de poços de petróelo verticais no pré-sal. In *XII Congresso de Engenharia, Ciência e Tecnologia*, Maceió, Brasil. Universidade Federal de Alagoas, Centro de Tecnologia, Programa Especial de Capacitação Discente, 2021.

[8] E. Poiate, A. M. Costa, and J. L. Falcao. Well design for drilling through thick evaporite layers in Santos basin – Brazil. In *IADC/SPE Drilling Conference*. Society of Petroleum Engineers, 2006.

[9] A. M. Costa, E. Poiate, C. S. Amaral, A. Pereira, L. Martha, M. Gattass, and D. Roehl. Geomechanics applied to the well design through salt layers in Brazil: A history of success. In *Multiscale and Multiphysics Processes in Geomechanics*, pp. 165–168. Springer, 2011.

[10] C. N. Araújo. Um modelo simplificado para a simulação do comportamento viscoso de rochas salinas para a previsão do fechamento de poços. Trabalho de Conclusão de Curso (TCC), Universidade Federal de Alagoas, Maceió, Brasil, 2009.

[11] C. N. Araújo. Desenvolvimento de um elemento finito para modelagem do comportamento de poços verticais em rochas salinas. 127 f. Dissertação (Mestrado em Engenharia Civil) – Centro de Tecnologia, Programa de Pós Graduação em Engenharia Civil, Universidade Federal de Alagoas, Maceió, Brasil, 2012.

[12] G. G. Gonçalves. Estudo paramétrico da influência da temperatura na análise termomecânica durante a escavação em rochas salinas. 117 f. Dissertação (Mestrado em Engenharia Civil) – Centro de Tecnologia, Programa de Pós Graduação em Engenharia Civil, Universidade Federal de Alagoas, Maceió, Brasil, 2011.