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Thermo-poroelastic numerical modeling of cement sheath structural integrity in oil wells

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Abstract. This study proposes a thermo-poroelastic numerical modeling approach to evaluate the structural integrity of the cement sheath in oil wells. Positioned between the casing and the surrounding formation, the cement sheath is responsible for casing support and hydraulic isolation between permeable zones throughout the well's lifecycle. Although thermoelastic models are commonly used in design practice, recent studies highlight that the porous behavior of hardened cement significantly affects its mechanical response under thermal and pore pressure variations. Analytical models provide valuable preliminary insights, but rely on simplifications that limit their applicability to real-world conditions. In contrast, numerical modeling enables more accurate representations of operational scenarios and stress distribution in the casing–cement–formation system. In this context, the methodology includes: (i) idealization of the physical model; (ii) characterization of the case study based on literature data; (iii) thermoelastic and thermo-poroelastic numerical modeling; and (iv) comparison of numerical results with analytical solutions. The results show excellent agreement with analytical predictions, with relative errors below 1.5%, confirming the accuracy of the adopted numerical approach. Therefore, the proposed numerical model represents a significant advancement in the structural integrity assessment of cement sheaths, supporting safer and more efficient well designs.

Keywords: Cement sheath integrity, Thermo-poroelasticity, Numerical modeling, Analytical validation, Oil wells.

1 Introduction

The cement sheath, positioned between the casing and the surrounding rock formation in oil wells, plays a fundamental role in maintaining structural integrity and ensuring fluid containment throughout the well's lifecycle. Failures in this primary barrier can result in unwanted fluid migration, jeopardizing operational safety and causing significant environmental and economic impacts [1, 2].

Maintaining the structural integrity of the sheath requires efficient mechanical design, which must adequately account for its response under different loading scenarios that may occur under real operating conditions. This assessment is essential to verify whether the mechanical properties of hardened cement are sufficient to withstand the thermal and mechanical stresses induced during the well's lifetime [3].

Once set, the cement sheath exhibits a porous network. When these pores are saturated with fluids, the material's mechanical response is altered [4]. Nevertheless, conventional cement sheath design often neglects such effects, treating hardened cement as a non-porous solid [5].

To investigate the implications of this assumption, Lins et al. [6] conducted an initial analytical study comparing thermoelastic and thermo-poroelastic approaches for the cement sheath. The results indicated that, depending on the type of loading, disregarding poroelastic behavior can lead to underestimation of stresses and structural integrity assessments that fail to predict certain failure conditions. However, that study incorporated poroelasticity only through Biot's coefficient, neglecting pore fluid flow.

More accurate analyses of poroelastic effects require models that account for hydromechanical interactions and more realistic wellbore cross-sectional geometries, such as primary cementing defects, casing eccentricity, and a broader range of loading conditions. In such cases, analytical approaches become limited, and numerical modeling emerges as a more feasible alternative.

Before advancing to more complex and comprehensive simulations, however, it is necessary to begin with simpler and validated strategies, gradually progressing toward more realistic scenarios. In this context, the objective of this work is to present a thermo-poroelastic numerical model performed in Abaqus® [7] software and verified against a known analytical solution, thereby establishing a reliable methodological foundation for future studies involving more complex and realistic investigations of poroelastic effects on cement sheath structural integrity.

2 Methodology

The methodology adopted in this study is organized into four main steps: (i) idealization of the physical model of the problem; (ii) characterization of the study scenario based on data from the literature; (iii) thermoelastic and thermo-poroelastic numerical modeling; and (iv) comparison of the numerical results obtained with analytical solutions. The following subsections provide a detailed description of each of these steps.

2.1 Physical model idealization

The physical model is idealized by representing the cross-section of an oil well, in which the casing, cement sheath, and rock formation are modeled as three hollow concentric cylinders (Fig. 1). In this configuration, the following loads are applied: internal pressure in the casing (P_i), external pressure from the formation (P_o), temperature (T), and pore pressure in the porous domains (P_p). Figure 1 illustrates this idealization, also highlighting the contact pressures that develop at the casing–cement (P_{12}) and cement–formation (P_{23}) interfaces as a result of the applied loads.

To complement the geometric description of the system, the following characteristic radii are defined: r_i (inner casing radius), r_{12} (casing–cement interface), r_{23} (cement–formation interface), and r_o (outer formation radius).

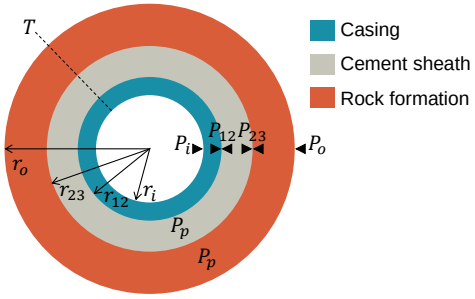


Figura 1. Representation of the well cross-section composed of the casing, cement sheath and rock formation

To enable the modeling of the problem, a set of simplifying assumptions is adopted. Small strains and displacements are assumed, allowing the use of linear elasticity theory. The materials are considered homogeneous, isotropic, and perfectly bonded to each other. The problem is formulated under plane strain conditions, restricting the analysis to the well cross-section. The casing is modeled as thermoelastic, while the cement sheath and adjacent formation are modeled as thermo-poroelastic materials. Thermal variations are applied through predefined temperature fields, assumed uniform within each domain. Pore pressure is prescribed as a boundary condition, so the porous response is incorporated only through Biot's coefficient, without explicitly modeling fluid flow. In addition, body forces are neglected in the formulation of the problem. However, the vertical stress includes the contribution of the rock formation weight, while the casing and cement sheath weights are disregarded.

2.2 Study scenario characterization

The study scenario adopted in this work is based on the loading conditions proposed by Joulin et al. [8], which describe six operational events characterized by variations of internal pressure in the casing, temperature across the cross-section, and pore pressure in the porous regions of the cement sheath and the rock formation. For the purposes of this analysis, three of these events are selected, as presented in Table 1, since they represent critical situations for assessing the structural integrity of the cement sheath.

Tabela 1. Loading condition for the well life-cycle events considered

Operational event	Reservoir pressure (MPa)	Internal casing pressure (MPa)	Well temperature (°C)
Start of production	44.3	44.3	121.0
End of production	2.0	2.0	121.0
Start of injection	2.0	2.0	4.0

The rock formation is subjected to an overburden stress of 83.8 MPa. For this lithology, it is assumed that the vertical overburden induces an average horizontal stress of 58.6 MPa, which is applied as a boundary load on the outer wall of the formation in the numerical model. The geometric properties and mechanical parameters adopted for the casing, cement sheath, and formation at this depth are detailed in Table 2.

Tabela 2. Properties of the components of the evaluated well section

Parameter	Casing	Cement sheath	Rock formation
Type	Steel	Class G	Sandstone
Inner radius (cm)	15.71	17.78	21.27
Outer radius (cm)	17.78	21.27	157.07
Young's modulus, E (GPa)	200.00	15.00	18.79
Poisson's ratio, ν (-)	0.27	0.25	0.20
Biot coefficient, α (-)	–	0.75	0.80
Thermal expansion coeff., β ($°C^{-1}$)	1.30×10^{-5}	9.00×10^{-6}	1.00×10^{-5}

2.3 Thermoelastic and thermo-poroelastic numerical modeling

The numerical modeling is carried out using the finite element software Abaqus®. Taking advantage of geometric and loading symmetry, the analysis is restricted to the upper-right quadrant of the cross-section (Fig. 2).

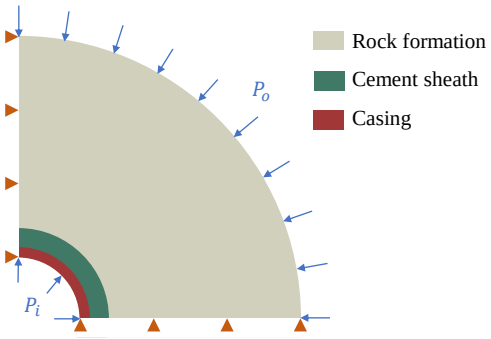


Figura 2. Geometry, boundary conditions, and loads adopted in the numerical model

The numerical procedure is divided into two stages. First, all materials are considered thermoelastic, which allows verifying the proper implementation of the thermomechanical part of the problem. Then, the thermo-poroelastic modeling is performed, in which the cement sheath and the formation are treated as porous materials, making it possible to evaluate the consistency of Biot's coefficient representation. In Abaqus®, this coefficient is not introduced directly, but rather defined through the bulk modulus of the solid grains K_s, according to the relation:

$$K_s = \frac{E}{3(1-2\nu)(1-\alpha)} \tag{1}$$

Other porous properties required by Abaqus®, such as void ratio, permeability, fluid unit weight, and pore fluid bulk modulus, are also defined, although they do not affect the results due to the assumption of no fluid flow.

The discretization of the model uses 100 elements in the tangential direction, while in the radial direction 8 elements are employed in the casing, 14 in the cement sheath, and 200 in the formation. For the latter, a bias factor of 25 is applied in order to refine the mesh in the vicinity of the cement sheath. The choice of element type and mesh refinement follows the convergence study presented in Lins [5], ensuring numerical stability and accuracy of the results without compromising computational efficiency.

To represent the thermoelastic behavior, finite elements of type `CPE8R` are used, which are eight-node quadrilaterals formulated for plane strain conditions, with biquadratic interpolation and reduced integration. For the thermo-poroelastic materials, `CPE8RP` elements are adopted, which maintain biquadratic interpolation for displacements and use bilinear interpolation for pore pressure, also with reduced integration.

It is worth noting that, for these elements, temperature is not treated as an additional degree of freedom, but rather prescribed as a uniform scalar field. Thus, thermal variations are introduced as external loading conditions, and not as internal variables of the finite element.

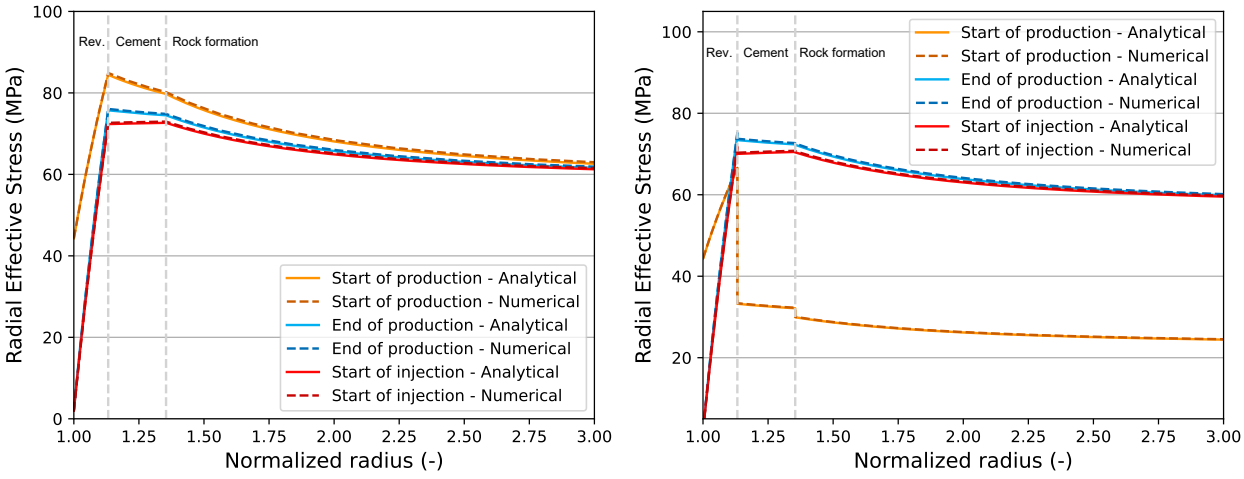
2.4 Comparison with analytical solutions

The results obtained from the thermoelastic and thermo-poroelastic numerical analyses are compared with the analytical solutions available for the equivalent problem, presented in Joulin et al. [8] and reproduced and adapted numerically in Lins [5]. The comparison is carried out considering the distribution of the radial, circumferential, and vertical effective stresses along the wellbore radius, allowing for a detailed assessment of the system behavior.

This procedure makes it possible to evaluate the fidelity of the numerical modeling against reference solutions, as well as to validate the representation of thermo-poroelastic behavior in Abaqus® for the simplified case under study.

3 Results and Discussions

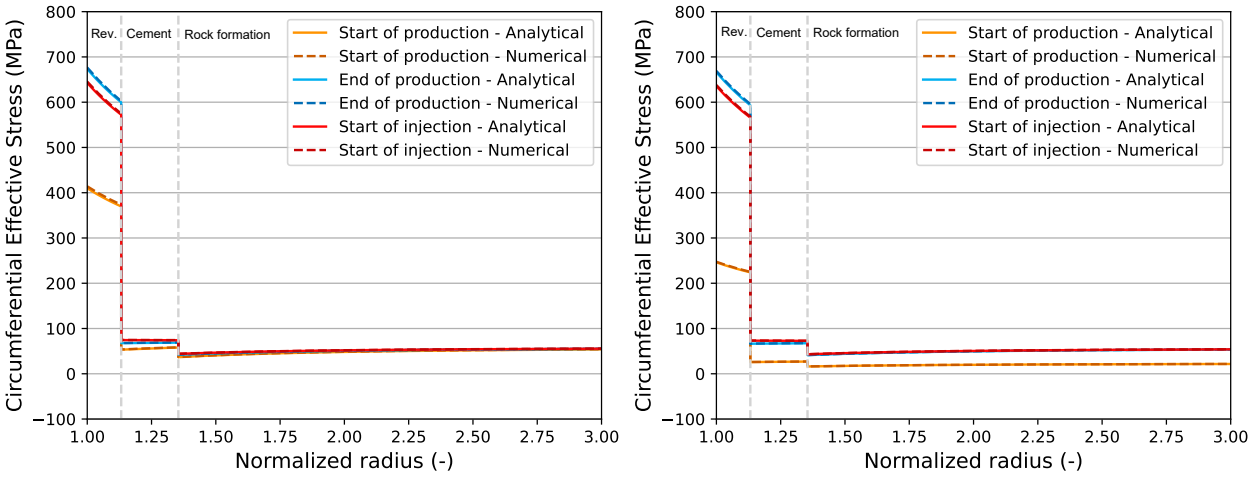
Figures 3, 4 and 5 present the comparison between analytical and numerical results for the thermoelastic and thermo-poroelastic analyses, corresponding to the radial, circumferential, and vertical directions, respectively. In all graphs, the results obtained from the analytical solutions are represented by solid lines, while the values extracted from the numerical modeling are indicated by dashed lines.



(a) Thermoelastic modeling

(b) Thermo-poroelastic modeling

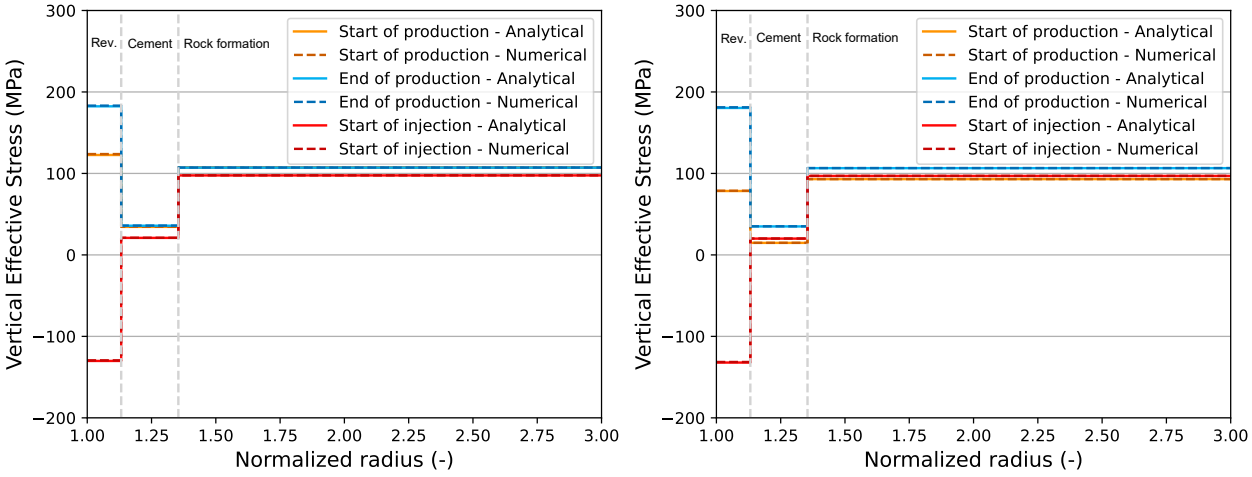
Figura 3. Analytical vs. numerical radial effective stress for the analyzed loading events



(a) Thermoelastic modeling

(b) Thermo-poroelastic modeling

Figura 4. Analytical vs. numerical circumferential effective stress for the analyzed loading events



(a) Thermoelastic modeling

(b) Thermo-poroelastic modeling

Figura 5. Analytical vs. numerical vertical effective stress for the analyzed loading events

Consistently, an excellent agreement is observed between the analytical and numerical approaches in both analyses. The curves show significant overlap, demonstrating the ability of the numerical modeling to adequately reproduce the thermal and mechanical effects and, in the thermo-poroelastic case, also the influence of pore pressure on the system behavior.

As a complement to the graphical evaluation, tables are presented to quantify the differences between the numerical and analytical results at points located at the extremities and at the interfaces of the system. Tables 3 and 4 compile, respectively for the thermoelastic and thermo-poroelastic analyses, the relative errors obtained at the following regions: inner wall of the casing, casing–cement interface, cement–formation interface, and outer wall of the formation. The errors are reported for each component of effective stress over the three simulated operational events.

The results indicate that, for most of the evaluated points, the relative errors remain below 1.5%, confirming the high accuracy of the developed numerical modeling. Therefore, the obtained results not only validate the numerical modeling for the simplified case under study but also provide confidence for its application in more realistic scenarios, where the absence of analytical solutions becomes a limitation. In this sense, the agreement verified between the approaches represents a fundamental step towards the use of thermo-poroelastic modeling as a tool for assessing the structural integrity of cement sheaths under more complex geometric and operational conditions.

Tabela 3. Relative error (%) of numerical results compared to analytical solutions for effective stresses in the radial (σ_r), tangential (σ_θ), and vertical (σ_z) directions, across their events, for the thermoelastic approach

Analyzed point	Domain	Start of production			End of production			Start of injection		
		σ_r	σ_θ	σ_z	σ_r	σ_θ	σ_z	σ_r	σ_θ	σ_z
Inner wall of casing	Casing	0.01	1.02	0.92	0.45	0.47	0.47	0.43	0.43	0.58
Casing–cement interface	Casing	0.53	1.01	0.92	0.43	0.47	0.47	0.39	0.44	0.58
Casing–cement interface	Cement	0.53	0.81	0.64	0.45	0.47	0.46	0.42	0.37	0.70
Cement–formation interface	Cement	0.56	0.74	0.64	0.43	0.47	0.46	0.42	0.38	0.70
Cement–formation interface	Formation	0.54	0.78	0.13	0.43	0.51	0.10	0.39	0.43	0.10
Outer wall of formation	Formation	0.00	1.23	0.13	0.00	0.92	0.10	0.00	0.82	0.10

Tabela 4. Relative error (%) of numerical results compared to analytical solutions for effective stresses in the radial (σ_r), tangential (σ_θ), and vertical (σ_z) directions, across their events, for the thermo-poroelastic approach

Analyzed point	Domain	Start of production			End of production			Start of injection		
		σ_r	σ_θ	σ_z	σ_r	σ_θ	σ_z	σ_r	σ_θ	σ_z
Inner casing wall	Casing	0.01	0.51	0.43	0.44	0.45	0.45	0.42	0.42	0.54
Casing–cement interface	Casing	0.20	0.50	0.43	0.41	0.46	0.45	0.38	0.42	0.54
Casing–cement interface	Cement	0.40	0.50	0.44	0.45	0.46	0.45	0.42	0.36	0.69
Cement–formation interface	Cement	0.42	0.48	0.44	0.45	0.45	0.45	0.41	0.37	0.69
Cement–formation interface	Formation	0.36	0.50	0.43	0.42	0.50	0.10	0.38	0.42	0.09
Outer formation wall	Formation	0.08	0.91	0.04	0.00	0.91	0.10	0.00	0.80	0.09

4 Conclusions

The numerical modeling carried out in this study showed excellent agreement with the analytical results, both for the thermoelastic and the thermo-poroelastic approaches. The relative errors obtained in the comparisons were, in most cases, below 1.5%, reinforcing the reliability of the methodology employed. Therefore, the numerical results proved to be suitable for representing the stress distribution and the structural behavior of the cement sheath under different loading conditions.

Although the analyzed configuration corresponds to a simplified case with a known analytical solution, the study conducted constitutes a fundamental first step toward more complex modeling approaches. The verification achieved provides a solid basis for the application of the thermo-poroelastic approach in scenarios where the absence of analytical solutions becomes a limitation. Thus, this work contributes to consolidating the use of numerical tools for investigating the structural integrity of cement sheaths in oil wells.

Based on the results obtained, the following topics are recommended for future work in order to improve the numerical modeling:

- Application of the proposed methodology to systems with multiple casings and cement sheaths, including ovalized geometries and cases with eccentric casings, in order to reproduce more realistic field conditions;
- Analysis of structural integrity in scenarios of poor cementing, considering uncemented or partially filled regions, representative of primary cementing failures; and
- Evaluation of the influence of variations in the mechanical and porous properties of the cement sheath on the structural response of the system.

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