XLVI CILAMCE
VITÓRIA - ES - BRAZIL - 2025
XLVI IBERO-LATIN AMERICAN CONGRESS ON COMPUTATIONAL METHODS IN ENGINEERING

Numerical simulation of thermal consolidation in a clayey rock formation towards well plug and abandonment

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Abstract. At the end of a well's lifespan, proper plug and abandonment (P&A) procedures are crucial to establish sealing barriers in order to prevent fluid leakage. Under certain conditions, salt and some clayey (shales) rock formations can close around the casing and form a geological barrier. To promote the formation of a shale barrier, activation techniques such as well pressure reduction, heating, and chemical stimulation can be adopted. While rock creep is often the standard approach, the mobility of clayey rocks may also happen by thermal consolidation, in which heating leads to the deformation of both the rock matrix and the pore fluids. This study assesses by means of numerical simulations the thermal consolidation induced by a heat source inside a well to be abandoned. Emphasis is placed on the impact of the permeability (from 10^{-17} to 10^{-21} m²) on the displacements and pore pressures generated around the well. It was observed that lower permeability led to higher pore pressure increases and longer times to reach the peak value. These simulations provided insights into the formation's integrity and the sealing performance of shale barrier for well P&A.

Keywords: Clayey rock, Shale, Thermal consolidation, P&A, Computational Geomechanics.

1 Introduction

Clayey rock formations have shown potential to function as engineered geological barriers due to their very low permeability and self-healing capacity in the area of nuclear waste disposal [1]. The area of well plug and abandonment (P&A) has also recognized such properties besides the time-dependent deformation and ductility of some clayey rocks [2], [3] with the purpose of leveraging casing embracement by the surrounding rock forming a barrier, and successful cases have been observed in the field [4]. Exposing the clayey formation to activation mechanisms such as pressure reduction, chemical stimulation, and thermal loading may trigger and/or accelerate the time-dependent deformation [5]. Although the mobility of clayey rocks is very often broadly referred to as "creep", this behavior can also be induced by thermal consolidation (i.e. the coupled response of the rock matrix and pore fluids when the rock formation is heated), promoting well closure.

In the context of well P&A, thermal effects on shales—actually a broad term to refer to clayey rocks—to stimulate deformation have gained interest. Stavland [6] showed that prolonged heating causes significant, often irreversible, deformation toward the well, influenced by stress anisotropy and very low permeability. Xie et al. [3] combined lab experiments and finite element (FE) models, confirming well closure under thermal loading. However, increased permeability and a lack of pore pressure replication in the numerical model indicated that heating alone might not guarantee hydraulic sealing. van Oort et al. [2] pointed out that clayey rocks exhibit thermal hardening i.e. initial expansion followed by contraction due to thermal plasticity. This behavior was confirmed experimentally, with no structural post-heating damage and possible self-healing effects preventing cracking [2]. Experimental and numerical results presented by Bauer et al. [7] support the potential of thermally

inducing deformation in shales for well sealing applications. Through undrained heating lab experiments significant pore pressure increase is observed causing relatively large plastic strains and, in some cases, brittle rock failure. Numerical simulations also suggest heating of the formation may produce an annular barrier, but highlights the importance of further studies. While brittle deformation may lead to barrier formation, it can compromise its sealing capacity.

In terms of simulation, the behavior of saturated porous media under thermal loading has been studied for decades, yet analytical solutions remain limited due to the complexity of thermo-hydro-mechanical (THM) coupled behavior. Early work by Witherspoon et al. [8] applied the FE method to benchmark problems, building on theories by Terzaghi [9], Biot [10], and others. Aboustit et al. [11] advanced the field with a FE formulation incorporating thermoelastic consolidation and validated it against in-situ gasification experiments. Booker and Savvidou [12] introduced an analytical solution for heat-induced consolidation, revealing the role of differential thermal expansion in the development of pore pressure excess. Their solution, later improved by Chaudhry et al. [13] due to noted inaccuracies, remains a key benchmark. Further developments included accounting for anisotropic permeability—crucial in sedimentary formations—and applying the FE method to cylindrical heat sources [14], [15] with results being deemed satisfactory. Cui et al. [16] presented a fully coupled THM FE formulation for saturated soils, validated by benchmarks and lab tests. Advanced methods such as the iterative coupling between temperature and the fully coupled displacement-pore pressure fields, and the Streamline Upwind Petrov-Galerkin (SUPG) were adopted, presenting advantages over the standard approaches for THM problems. Another study by Li et al. [17] addressed the effect of local thermal non-equilibrium (LTNE) in THM problems, revealing critical insights into fluid-solid temperature differences and their impact on stress and pore pressure.

This study addresses the thermal consolidation of clayey rocks applied to the context of P&A by means of numerical simulations employing the FE method. The simulator Abaqus® is adopted, and a coupled THM formulation applies. Firstly, the analytical solution for a deep buried point heat source [13] is implemented as benchmark. Then, numerical simulations evolving from this benchmark to a well with a cylindrical heat source placed at its bottom are carried out. The permeability is selected as a key property whose impact in the overall response is analyzed. The results provide valuable insights into how clayey rocks respond under thermal loads and highlight the sensitivity of the thermal consolidation to permeability.

2 Modeling and simulation benchmark

The analytical solution for the primary variables (i.e. displacement, pore pressure and temperature) of this specific coupled THM problem was presented by Chaudhry et al. [13]. This approach assumes the following hypotheses: i) spherically symmetric model with a buried point heat source centralized in the model; ii) thermo-porous-elastic formation; iii) low fluid flow velocities; iv) heat flow only by conduction; v) fully saturated model; vi) gravitational forces neglected; vii) solid and fluid intrinsically incompressible; and viii) constant parameters, not sensitive to temperature. The equations and parameters adopted are available in the above-cited reference and were not transcribed here for the sake of brevity. In short, the analytical solution depends on the porous-elastic parameters of the rock formation, fluid properties, and thermal parameters of both. The model initializes with null temperature, pore pressure and displacements – hence the changes in these field variables are predicted. The analytical solution [13] is implemented by the authors in a Matlab code and successfully benchmarked, Fig. 1. In this figure, T, P, U1 and U2 stand for temperature change, pore pressure change, and horizontal and vertical displacements, respectively.

Using a point heat source is a more conceptual application, which not only may introduce convergence issues in the numerical solution as it triggers strong and localized temperature and pore pressure changes, but also is not realistic. Hence, the power of the point heat source was divided by the volume to apply an equivalent heat generation. The models are axisymmetric and consider half-space, and boundaries sufficiently far from the heat source in order to avoid spurious boundary effects. Quadrilateral elements supporting fully coupling temperature-pore pressure -displacement fields (linear interpolation for all fields) are adopted.

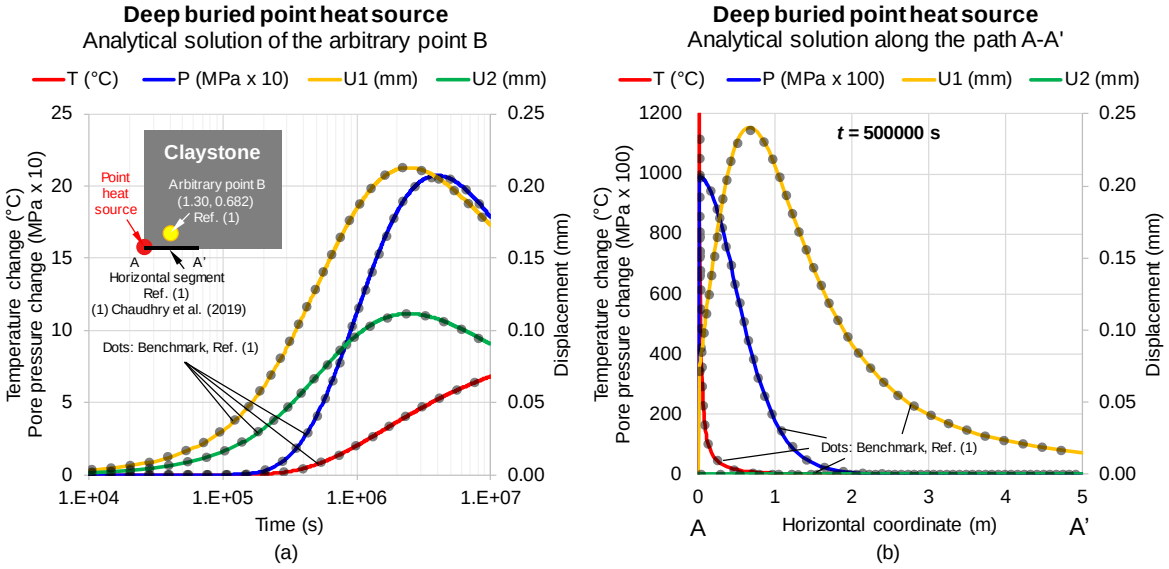


Figure 1. Benchmark of the analytical solution of the coupled THM problem. Results at point B (a) and along the horizontal path A-A' (b). The solid lines represent the results from author's implementation and the dots those from Chaudhry et al. [13]

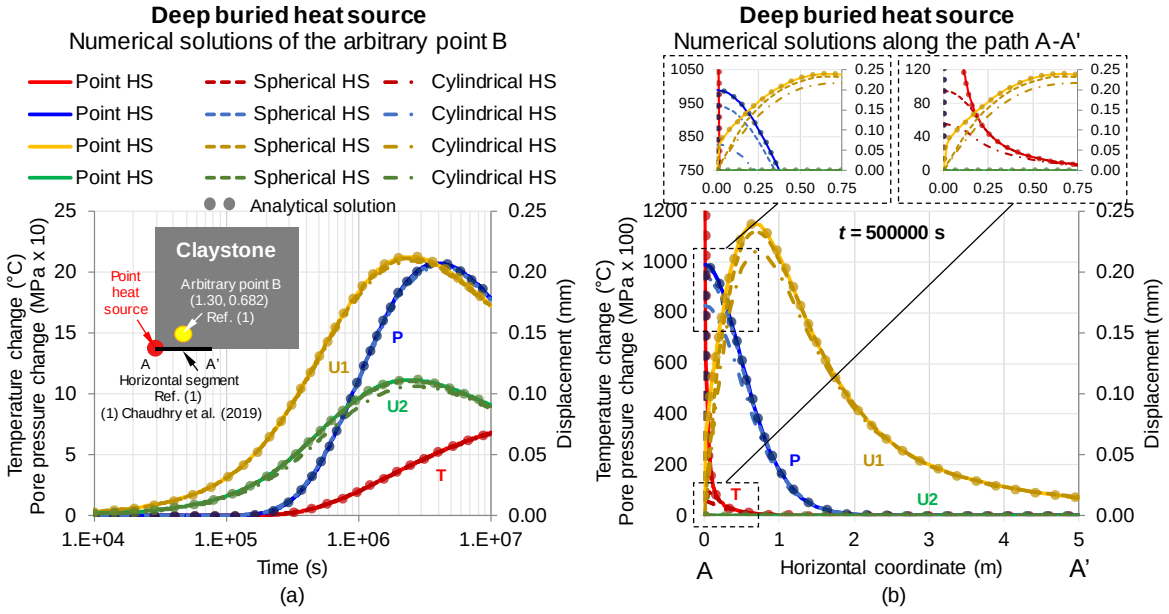


Figure 2. Comparison among the analytical (author's implementation) and numerical solutions for the point heat source (HS) problem, and numerical solutions for equivalent volumetric HSs (spherical and cylindrical). Results at point B (a) and along the horizontal path A-A' (b)

Figure 2 presents the comparison among the results obtained with the analytical solution (only the authors' implementation is shown) and three numerical solutions: point, spherical and cylindrical heat sources. In this figure, T, P, U1 and U2 represent the same quantities as in Fig. 1. In essence, the results differ little very, only around the heat source generator according to the geometry adopted. When volumetric sources are adopted, the temperature increase is more dispersed, spreading more throughout the generator geometry, justifying the lower peak values. A little far from the generator, all the solutions converge to the same values. This response is

physically coherent and further supports the numerical models to be adopted in the next section.

3 Application

3.1 Overview

A conceptual model of a well to be abandoned using a shale barrier is considered as a practical application to study the impact of the thermal consolidation. The well is 12 1/4 inches in diameter (31.115 cm). A cylindrical heat source of capacity of 260 W and 0.6 m in length [18] is placed at the well bottom. In order to simplify modelling, this source is assumed with the same diameter of the well.

The simulation assumes initial conditions compatible with the depth 3820 m [19]. The vertical stress is 49.53 MPa and horizontal stresses are 47.63 MPa (total compressive stresses). Besides that, the pore pressure and temperature are 38.55 MPa and 30.6ºC, respectively [19]. This initial state is assigned to the numerical model ensuring negligible deformation. Then, the well is drilled using a fluid of 8.6 ppg (10.1 kN/m³) [19], resulting in an elastic response caused by the stress relief around the well wall. After drilling, the heat source is activated and acts over a simulation time of one year. A pore pressure build-up occurs due to heating, and this leads to stress and strain changes. The modelling space, geometry aspects and FE type from Section 2 apply.

The shale formation is assumed as a thermo-elastic perfectly-plastic material. Plasticity follows using the Mohr-Coulomb criterion. The Callovo-Oxfordian (COx) claystone is adopted as the reference material for the simulations. For the sake of brevity, Tab. 1 lists only the rock parameters adopted in this application which differ from those in the work of Chaudhry et al. [13]. These parameters are assumed to be insensitive to temperature. Five different permeabilities are tested within a reasonable range for clayey rocks.

Table 1. Shale (represented by the COx claystone) and fluid parameters which differ from those in Chaudhry et al. [13]

Parameter	Symbol	Value (unit)	Reference
Density	ρ_s	2695.0 (kg/m³)	[20]
Porosity	ϕ	0.2857	[19]
Permeability	K_{perm}	10^{-17} to 10^{-21} (m²)	Assumed by the authors
Bulk modulus	$K_{Bulk,s}$	10^{9} (GPa)	Assumed to obtain Biot's coefficient = 1
Bulk modulus of water	$K_{Bulk,w}$	2.4 (GPa)	[19]
Young's modulus	E	8.77 (GPa)	Calculated from Zhang et al. [20]
Poisson's ratio	ν	0.23	Calculated from Zhang et al. [20]
Cohesion	C	9.0 (MPa)	[20]
Friction angle	φ	19.0 (°)	[20]

3.2 Results

Firstly, a comparison between the analytical (without a well) and numerical (with well) solutions is carried out. Although these solutions are not fairly equivalent, they are plotted together in order to outline how far a simplified analytical approach for this THM problem would be from a realistic well model application. To this end, the permeability value of 10^{-17} was adopted.

The results are shown in Fig. 3. The temperature evolution (T) follows a similar trend in both models. However, the analytical solution considers a point heat source and numerical model assumes a volumetric heat source, which leads to a smoother temperature distribution close to the heat source than the former. As a result, the peak temperature in the analytical solution is very high and concentrated at the heat source coordinate. According to the analytical results in Fig. 3 (a), point D moves away (positive displacements, U1 and U2) from the heat source over time. Pore pressure (P) begins to dissipate shortly after a day. The vertical displacement (U2) predicted by both models shows good agreement, indicating that the well does not significantly affect the vertical displacement field. However, point D tends to move slightly toward the center of the well (negative displacement), as reflected in the horizontal displacement (U1). The initial value of U1 is credited to well drilling since the initial

state is assigned in such a manner that essentially null displacements are generated, and the subtle evolution of well closure is attributed to heating.

After a year, the results along the horizontal axis show that both P and U1 are greater in the analytical solution and decrease with distance from the heat source. The increase in pore pressure is small considering the absolute values, but it would be visible if only pore pressure changes were presented. In contrast, the numerical results show an initial increase in both P and U1, reaching a peak before decreasing. Throughout the entire domain, the values predicted by the analytical solution remain consistently higher than those from the numerical simulation, especially near the heat source.

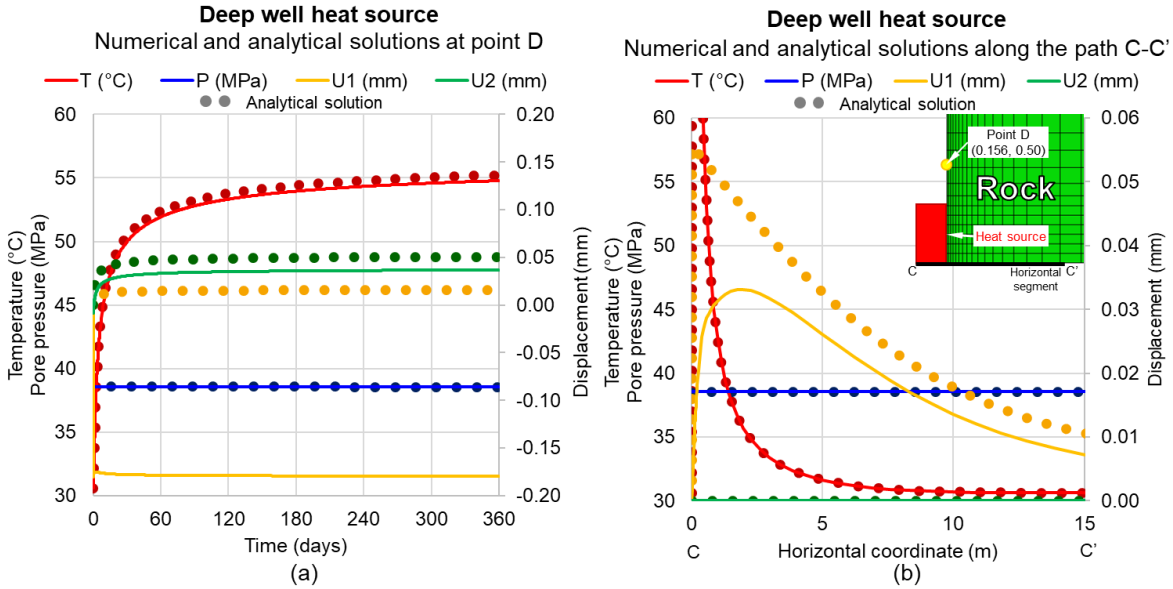


Figure 3. Comparison between numerical (solid lines) and analytical (dots) solutions of the coupled THM problem. Results at point D (a) and along the horizontal path C-C' (b)

Secondly, since the numerical solution led to coherent results additional numerical simulations were conducted to evaluate the behavior of a well under thermal stimulation considering five different formation permeability values: 10^{-17}, 10^{-18}, 10^{-19}, 10^{-20} and 10^{-21} m².

The well closure and the pore pressure in the formation were represented, Fig. 4. Like the previous simulation, the displacement measured at point D (well wall, Fig. 4 (a)) initially shows a sharp increase, which is attributed to elastic deformation due to drilling. A secondary stage of closure is linked to heating and the consequent pore pressure excess. This latter component of deformation varies depending on the permeability of the formation. While differences are noticeable during the simulated time span, the curves suggest a possible convergence in closure values by the end of the simulation. Although not included for the sake of brevity, stress paths close to point D are also analyzed. These show progressive evolution of the mean and deviatoric stresses, but, no plastic deformation is observed, which would otherwise lead to larger displacements and irreversible deformation. Future studies adopting plasticity models with cap may better capture the onset of plasticity and its effects on the material deformation.

The pore pressure is evaluated at a point E located approximately one meter (0.977m) from the well wall and 0.5m above the center of the heat source. The point at the well wall (D) is not selected for this evaluation because of the assumed drained boundary condition. It is observed that the location of maximum pore pressure moves closer to the well as permeability decreases. Fig. 4 (b) reveals that, by the end of the simulation, the peak pore pressure occurs a few meters away from the well. The lower permeabilities lead to higher peak pore pressures and delay the time at which these peaks are reached – note the peak values and corresponding times indicated in red in Fig. 4 (b). This behavior is consistent with the slower fluid dissipation rates associated with lower permeability materials, and highlights the importance of accurate permeability characterization in the design and evaluation of thermal stimulation to trigger well sealing.

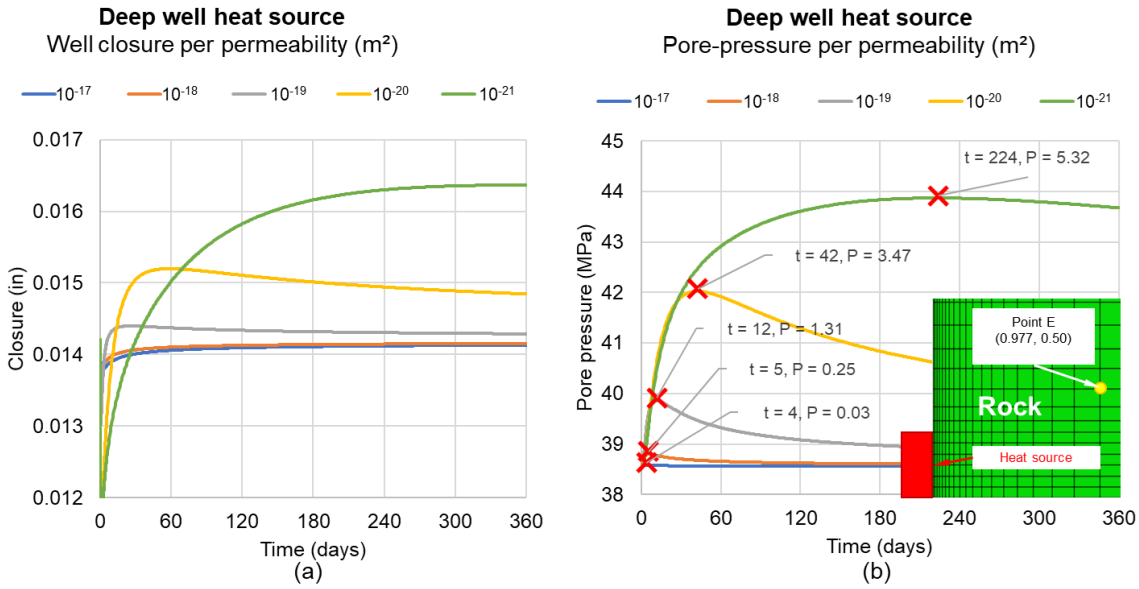


Figure 4. Evolution of well closure (a) and pore pressure (b) along 360 days of operation of a cylindrical heat source

4 Discussion and conclusions

This study addressed the area of thermal consolidation applied to well plug and abandonment with the formation of a shale barrier around the well. It replicated an existing analytical solution for a deep buried point heat source and adopted numerical simulations to evolve from this conceptual problem to the more realistic problem of a heated well surrounded by shale formation. The investigation focused on the influence of rock permeability on well closure and pore pressure evolution, which are critical responses to be assessed when considering the shale formation's potential to act as a geological barrier.

When analyzing deformation stimulation methods such as heating, one challenge is to define temperature increase ranges which are both feasible to be reached in the field by thermal heaters working during reasonable periods and sufficient to lead the formation to deform significantly. The temperature increase in the simulations presented in this study was around 25 °C, aligning with realistic values in engineering operations, as supported by literature such as van Oort et al. [2] and Guiltinan et al. [18].

The well closure values in the models considered were still low to form a barrier. If the models included an uncemented casing of 9 5/8 inches in outer diameter for instance, the annulus space of 2.625 inches would not yet be closed. This may be explained by the absence of plastic deformation under the tested conditions, Moreover, the simulations demonstrated that lower permeabilities lead to higher pore pressures excess and longer time spans to reach peak values.

Considering the hypotheses taken and the findings of this study, further exploration of alternative mechanical constitutive models addressing failure mechanisms other than shear is needed (e.g. models with cap). Even if larger displacements occur, there is still the question of whether a plasticized rock formation would be able to offer sufficient hydraulic isolation and act as a barrier. The sensitivity of the mechanical, hydraulic and thermal parameters/properties on temperature is another aspect to be investigated.

Acknowledgements. This research was carried out in association with the ongoing R&D project registered as ANP no. 23659-6, “SABAR” (PUC-Rio/Petrobras/ANP) sponsored by Petrobras under the ANP R&D levy, Brazil as “Compromisso de Investimentos com Pesquisa e Desenvolvimento”.

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