Integrated Computer-Aided Design for Well Cementing: Analyzing Containment in Deepwater Wells

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Abstract. This study investigates the impact of numerical simulations on cement integrity during the drilling of deepwater top holes through salt formations. The primary aim is to enhance well containment analysis by optimizing cement sheath quality. We begin with a comprehensive literature review, examining industry practices for drilling and cementing in salt zones. By analyzing existing literature, we gain insights into best practices and challenges related to cementing in deepwater wells. Next, we leverage field data from hundreds of wells in the Santos Basin pre-salt region. This data allows us to identify critical aspects affecting cement quality and determine the main variables to be considered. The heart of our approach lies in real-scale numerical simulations using chemo-thermo-mechanical finite-element models. These simulations guide our design process, considering factors such as well geometry (inclination, tortuosity, and hole enlargement) and different cement slurry properties. Importantly, the simulations also account for severe thermal and mechanical stress during worst-case discharge and shut-in scenarios. By ensuring effective well-control containment, we ensure that the casing cement will not fail in the event of a blowout. For geometry requirements, meeting specific well geometry criteria is essential for achieving the desired cement sheath quality. As for cement slurry design, simulations indicate that salt-based cement slurry is favored due to its superior bond strength and field performance. We also evaluate the impact of cement expansion and shrinkage for different scenarios, showing the enhanced performance of expansive cement in long-term integrity. Integrating simulations into standard cementing practices offers significant advancements in maintaining deepwater well integrity. By optimizing cement sheath quality, we enhance well containment and contribute to safer drilling operations in challenging environments.

Keywords: well cementing, mechanical integrity, cements.

1 Introduction

Deepwater well design practices in Brazilian Pre-salt allow riserless drilling to be performed up to the top of the salt layer, which significantly reduces drilling time by decreasing the number of phases in the wells. The subsequent phase reaches the top of the payzone with a riser. This strategy requires effective annulus isolation of the last riderless-run casing so that the salt section is drilled with a high-density drilling fluid to prevent excessive salt creep and its consequences. It also requires that the casing and its annulus cement withstand all other service and survival loads until the next casing is run and cemented. Typical survival loads include events followed by uncontrolled blowouts.

In the worst-case situation, the initial overbalance pressure from the drilling fluid hydrostatic pressure may be lost (due to severe loss or a BOP disconnection) and fluid from the reservoir may migrate into the well, eventually filling the volume up to the BOP. Thus, the pressure and temperature inside the surface casing will increase substantially, and the loads will be seen by the cement sheath. The Well Containment Analysis (WCA) for the cement sheath needs to ensure the well will survive an uncontrolled blowout at the mudline and that shutting in the blowout via a capping stack is also possible, avoiding the leak path through the annulus. Figure 1 summarizes the well condition at the shut-in and the load case for containment evaluation.

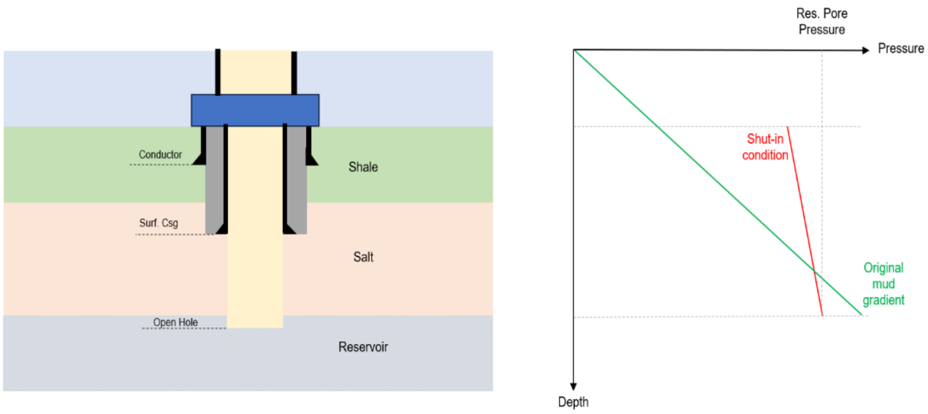

Figure 1. Well condition and load case for containment evaluation (Source: Authors)

Although the surface casing is typically fully cemented, the top of hydraulic isolation (HID) usually stays in the first 200m above the shoe. The HID provides input for the casing design, but this information itself offers little information on the contribution of the cement quality to the well barrier system. Considering the specific challenges involved in riserless and salt drilling and cementing – in this case, combined – this work addresses the requirements for the assessment of the reliability of annulus cement for pressure-containment and structural purposes, focusing on mechanical integrity.

2 Salt zone cementing in pre-salt wells.

Evaporitic deposits show excellent properties for trapping oil and gas reserves, and in Brazil, the salt layer typically ranges from 500m up to 3500m length (Moreira [1]). This section summarizes the best practices for cementing in front of salt zones.

2.1 Challenges for Cementing Salt Zones

Among the challenges involved in pre-salt wells, well cementing in front of salt zones has been one of the most relevant due to its role in well integrity. Creep and solubility of salt are characteristics and behaviors that require special attention, and both depend on several characteristics, such as chemical composition (mineralogy), in situ stresses, and temperature. Both need to be assessed in every well design as follows:

- Creep occurs during salt drilling due to stress imbalances in the well. Creep rates may reduce and deform the wellbore diameter and impose difficulties on drilling or running casing (stuck tubular, high drag loads, or buckling), damage casing centralizers, decrease standoff, and increase ECD while circulating fluids in the well and beyond. These effects challenge cement placement and, if the annulus coverage of the cement sheath is poor, non-uniform loads on the casing are also to be considered in addition to static loads due to in situ stresses that can cause the casing to collapse. Creep is usually managed by selecting the proper fluid density approaching the overburden gradient when possible. Sylvite, Carnallite, and Tachyhydrite are among the highest creeping rates and Halite and Anhydrite (near immobile) are among the least. Deep and high-temperature sections of salt also tend to exhibit more intense squeezing behavior over short periods (API RP 96 [2]).

- Chemical and physical interaction of salt with the drilling and cementing fluids used in a well occurs during static and dynamic events. The dissolution of salt can generate hole enlargement and washouts in the wellbore, thus impacting casing centralization, compromising casing standoff, and sometimes compromising well trajectory if directional tools cannot work properly during drilling. High solubility is also a problem when salt is incorporated by cement slurries, which can also affect critical cement properties such as thickening time, rheology, and final compressive strength. To avoid excessive dissolution, fluid, spacer, and cement slurry properties and composition should be carefully chosen. Flow pump rates also have an impact on leaching during drilling and cementing. Carnalite and Tachyhydrite have water in their composition and are among the most soluble salts, while Halite and Anhydrate are the least. If heterogeneous layers of salt are present, it may also generate an irregular well caliper profile (Folsta [4], Amer [5]).

2.2 Industry practices on cementing in front of salt zones.

Although there are very different approaches and well-developed strategies with reported success, there are key considerations that may be addressed in a cementing design in front of salt zones. These are as follows.

Evaluation of subsurface salt conditions: understanding the mineralogy, pressure, and temperature conditions of salt that may affect its behavior of creep and dissolution. Having reliable data and models is key to properly defining the objectives and challenges of the casing running and cement job operations.

Drilling fluid selection: Water-based muds are commonly the only available choice in riserless drilling and a dual gradient is employed. Density should be selected to mitigate excessive creep rate and still provide a gradient below the fracture pressure of exposed formations above the salt. Salinity, rheology, and drilling parameters control the process of salt leaching/dissolution. Consensus exists that higher salinity and laminar flow lead to lower dissolution, but rheological properties should be managed to avoid excessive pressure in the well that could induce losses above the salt and compromise the well cleaning process. Also, a saturated fluid at surface conditions may be unsaturated at depth depending on the subsurface temperature and mineralogy of the drilled salt.

Cement slurry selection: selecting the appropriate cement slurry design, and chemical and physical properties for the objectives of the cement job of protecting casing from collapse and acting as a barrier in annulus for the desired application. In the salt environment, these properties can be affected by the incorporation of salt during pumping or curing in the well. Additionally, the leaching/dissolution is also affected by cement slurry composition (Simao et al, 2012 [6]). The content of salt in the cement slurry can be seen as a trade-off between minimizing dissolution with a high content of salt and obtaining delayed compressive strength and thickening time, decreased yield point, and plastic viscosity. Conversely, with low or intermediate salt concentration, the advantages and disadvantages are inverted. KCl provides better control on slurry properties but implies more challenging logistics since it is usually added in bulk, while NaCl is usually added as brine. Cement rheology needs to be adjusted to minimize leaching/dissolution and provide proper displacement efficiency.

Casing centralization and cement placement: Proper cementing and zonal isolation require that the cement slurry properly replaces the pad mud present in the well, which is true for cementing salt zones and all other operations. If the casing is not centralized, a wide side is formed in the annulus, and the mud displacement may become excessively challenging, if not unachievable (API, 2010 [3]). For that purpose, the use of centralizers from the shoe up to the desired HID is a consolidated practice. For salt zones, the possibility of hole enlargement is an obstacle to obtaining adequate casing centralization, especially with heavy casing and deviated wellbores.

3 Mechanical integrity of cement in different conditions.

A study on the cement sheath integrity under thermal and mechanical loads induced by wellbore shut-in was conducted using Finite Element Analysis (FEA) software to identify key aspects of wellbore geometry requirements as well as other influencing parameters.

These developed models consider the initial stresses on the cement sheath after placement and forces applied inside the casing due to temperature and pressure changes and can identify risks for debonding, tensile, or compressive failure which can lead to fluid leakage. However, due to assumptions made by the models and input data uncertainties, results should be taken qualitatively (API, 2010 [3]).

3.1 Mechanical behavior of cement and computational model

A computational tool (TENCIM®, as described in Filho et al [7]), which includes a strain-stress calculator for cement sheaths based on the finite-element method, was used. This method, widely used in solving elasticity numerical problems across various physics domains, models the system in a finite number of discrete elements as an approximation to the solution. The assumption for the model is unidimensional in the radial direction of the well (r, θ) and a plane state of deformation in the axial well direction (z), as shown in Figure 2.

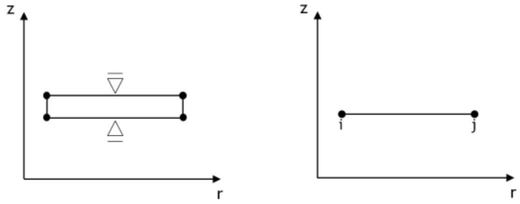

Figure 2. TENCIM 1D Simplification.

In this model, the governing equations are derived from the thermodynamic theoretical framework for porous media, considering the coupled effects of hydration reaction, temperature evolution, deformations, and changes in concrete properties. The main considerations are as follows:

- The cement is treated as a chemically reactive porous medium.
- Initially, it behaves as a fluid composed of free water and air, transitioning into a porous solid once it reaches its percolation threshold.
- In its solid phase, it consists of anhydrous cement and hydrates.

The model´s primary outputs are the residual tensile and compressive capacities, which reflect the ratio of the stress experienced by the cement sheath and its ability to withstand it. The residual capacity (RC) can vary between 0% and 100%, where 0% indicates that the cement has entered the plastic regime, and 100% represents a state of effectively zero stresses. Other important points related to residual capacity are:

- The sheath remains intact for any value greater than 0, although a safety factor should be adopted.
- A minimum residual capacity of 50% is recommended, corresponding to a safety factor 2.
- The safety factor reflects the high degree of uncertainty in these simulations.
- The simulation assumes a perfect cement sheath.
- Cycling effects (fatigue) are not yet considered in the simulation.

3.2 Modeling of load conditions

For the verification and validation cases of the computational code, a test protocol was defined, including a simulation plan for the wellbore scenario of a selected deepwater well, as shown in Figure 3.

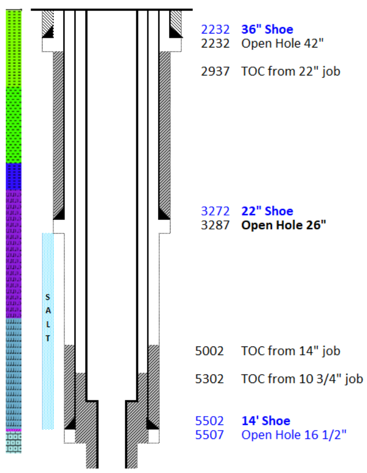

Figure 3. Well selected as deepwater representative scenario

The simulations included one casing typical large-bore configuration, tested with 2 cement slurry formulations from the mechanical and thermal properties database. Additionally, parametric sensitivities were simulated, resulting in several verification cases.

The protocol for executing the cases involved running a base case with the two different typical characterized slurries and running parametric sensitivities (+3 simulations for each case). Table 1 shows the configurations of the cases and the parametric sensitivities.

Table 1. Load cases and parametric sensitivities.

Large Diameter in Open Hole Casing 22" in 26" hole	1. Variable sheath thickness (0.5x and 1.5x) simulating 50% standoff; 2. 0,5% Shrinkage in Cement 3. Variable thermal loads (+ 30ºC heating during blowout). 4. Variable pressure load (+2000 psi during blowout)

Table 2 and Table 3 show, respectively, the values of the mechanical properties of the cement slurries and the thermal properties of the reference formulation used in the simulations.

Table 2. Mechanical Properties of Cement Slurries.

Nº	Tensile Strength (Pa)	Elastic Modulus (E) (GPa)	Poisson's Ratio (ν)	Friction Angle (°)	Cohesion (MPa)
1	3.70E+06	17.0	0.26	19.5	11.1
2	1.72E+06	4.9	0.19	7.9	9.1

Table 3. Thermal Property of Reference Slurry.

Coefficient of Thermal Expansion (°C⁻¹)	Thermal Diffusivity (W/m·K)	Thermal Capacity (J/m³·K)	Activation Energy (J/mol)	Latent Heat of Hydration (J/kg)
9.00E-06	0.544	1.97E+06	3430.0	5.65E+08

Table 4 presents the thermal and mechanical properties of the base formation (halite).

Table 4. Mechanical and Thermal Properties of Formations.

Type	Elastic Modulus (E) (Pa)	Poisson's Ratio (ν)	Thermal Expansion (°C⁻¹)	Thermal Diffusivity (W/m·K)	Thermal Capacity (J/m³·K)
Halite	20.4E+09	0.36	1.0E-5	6.006	1.9E+06

To facilitate and standardize data entry into the code, boundary conditions for the initial temperatures and stresses were determined, as shown respectively in Table 5 and Table 6.

Table 5. Initial Temperatures of the system.

Casing interior	End of Cementing (interior)
Steel	$T(r) = T_i + \frac{T_o - T_i}{\frac{\ln r_o}{\ln r_i}} x \ln \frac{r}{r_i}$
Casing exterior	End of Cementing termal profile (annular)
Cement Sheath	End of Cementing termal (annular)
Cap Rock	$T(r) = T_i + \frac{T_o - T_i}{\frac{\ln r_o}{\ln r_i}} x \ln \frac{r}{r_i}$

For steel: T_o = Annular temperature T_i = Wellbore interior temperature.
For rock: T_o = temp. at r_o, T_i = Temperature in annulus, $r_o = r_{well} + 1$ m and constant temperature (geothermal gradient) $\forall\ r > r_{well} + 1$ m.

Table 6. Initial Stress State.

Steel	P_i = Pressure inside casing (internal fluid hydrostatic)
	P_o = Annular pressure (cement hydrostatic)
	σ_z = Axial stress in casing (Torque & Drag simulation)
Cement	Pi = Po = σz = Annular pressure (cement hydrostatic)
Cap rock	P_i = Annular pressure (cement hydrostatic)
	P_o = Horizontal stress in rock (fracture gradient)
	σ_z = overburden

3.3 Case study in real deepwater well – results and discussion

This section presents a detailed case study analysis of well cementing in a deepwater well, leveraging data from the TENCIM simulations conducted for the WCA well scenario. The case study aims to validate the simulation results and provide insights into the mechanical integrity of the cement sheath under varying conditions.

The WCA well, located in a deepwater environment, features a complex geological profile, including significant salt formations. The wellbore has a water depth of 1975 meters, and the casing configuration includes both an inner column and multiple casing layers designed to withstand high mechanical and thermal loads. The primary objective is to ensure effective well containment and prevent fluid migration in severe loading conditions, such as blowouts.

The simulations were configured to evaluate the mechanical behavior of the cement sheath under different thermal and mechanical load conditions. The following scenarios were analyzed:

- Initial Condition Without Load: Simulation of the cement sheath immediately after placement with no external loads.
- Pressure Testing: Sequential pressurization and depressurization to simulate well integrity tests. The surface pressure considered is 4000 psi and the internal fluid density is 8,55 ppg.
- Blowout Conditions: Evaluation of the cement sheath under high-pressure and high-temperature conditions simulating a blowout scenario. The reservoir temperature of 85ºC and pressure of 8500 psi is considered in the depth pf 3212m, which is 60m above the shoe.

The results are presented as follows. Figure 4 (at left) presents the radial and tangential stresses developed during the curing process of cement (first 48h) and at the end, the pressure test and blowout event indicate an inversion of the tangential stress signal, putting the inner cement sheath under traction. As a result, the remaining capacity for the Mohr-Coulomb criteria drops significantly during the pressurization events (Figure 4 at right). All stresses were calculated on the base of the cement sheath.

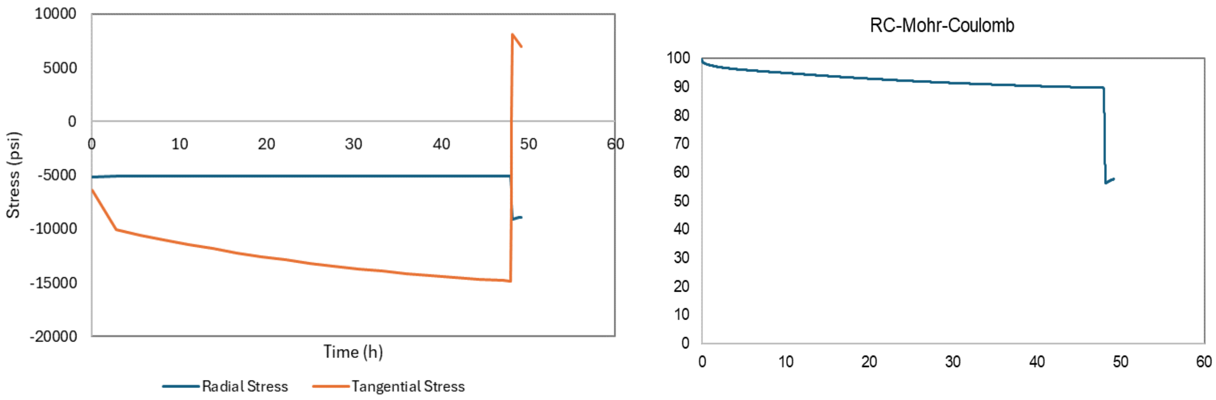

Figure 4. Stresses during curing (first 48h) and blowout event (at the end) at left. Remaining capacity for Mohr-Coulomb criteria on right

As for the sensitivity cases, Table 7 summarizes the minimum remaining capacity (RC_{min}) as per Mohr-Coulomb criteria. These results show that a moderate change in the standoff, in the temperature of the reservoir and the slurry mechanical properties imply in only minor changes int the remaining capacity. However, an increased pressure load and shrinkage in the cement slurry provoked large differences.

Table 7. Sensitivity cases

Case	**RC_{min}**
Base Case	0.5646
50% Standoff	0.5613
1% Shrinkage	0.0165
Slurry #2	0.5796
Increased Temperature Load	0.563
Increased Pressure Load	0.4114

It can be concluded that shrinkage and pressure loads are the main variables to influence its ability to withstand the defined loads due to their impact on initial stresses after the cement is cured. Non-shrinking cement provides better resistance on loads than a well-calibrated well with 70% standoff. Another important constraint in the results analysis is initial conditions in cement placement, such as contamination (which can lead to changes in mechanical properties) and the presence of defects in the cement sheath. In that way, keeping the wellbore quality is vital to ensure the analysis is valid.

4 Conclusions

The summarized analysis presented in this work confirms that the industry has developed robust knowledge of best practices for salt drilling, but riserless drilling of salt sections imposes additional challenges with cost and performance consequences. This study underscores the necessity of meticulous control over wellbore quality to ensure a reliable and durable annulus cement barrier in all well events, which should be seamlessly integrated into the overall cementing design.

Quality objective requirements were set, and when they were followed, the cementing design adopted in Brazilian pre-salt wells showed excellent field results with no failures and a good correlation with post-job analysis. This highlights the critical importance of adhering to established best practices and quality standards in the cementing process.

The importance of this analysis is to show that annulus hydraulic isolation provided by cement barriers plays a relevant role in the context of well containment and the well barrier system, considering critical deepwater well scenarios. As a measurable improvement by this analytical process, all wells cemented within the design conditions evaluated were properly verified during drilling operations, through cement bond log evaluation or pressure integrity tests (FIT).

In conclusion, the integration of rigorous simulation methodologies, adherence to best practices, and the use of advanced cement formulations collectively contribute to the successful management of deepwater wells. This comprehensive approach not only ensures well integrity but also optimizes operational efficiency, ultimately leading to safer and more cost-effective drilling practices in challenging environments.

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