

Analyzing Geomechanical Effects while Drilling Salt Wells through Numerical Modeling

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Abstract: Santos Basin is one of the most promising basins of Brazil, recently it was discovered light crude oil of 30° API (American Petroleum Institute), this reservoir of high productivity is located below a salt layer of two thousand meters of thickness. Salt also known as an evaporite rock is found in many hydrocarbon basins around the world. Evaporites are sediments formed initially from minerals dissolved in water, the most common are: halite, gypsum, and anhydrite. These minerals are found in areas that passed by a geological time of high evaporation or precipitation. Evaporites in general have the structure of a dome, formed when a thick layer of salt found in the bottom begins to crossover the superior layers vertically, its process delays millions of years. The presence of saline structures takes into favorable conditions for creating a trap for hydrocarbons, increasing the success of probability in oil and gas exploration. In salt drilling the main problem is the closing of the well or known as squeeze or salt pinch, this phenomenon provokes the imprisonment of the drillstring also known as stuck pipe. Evaporite rock behavior is defined through a creep model. The creep model is the term used in the bibliography to define the tendency that a material has to move or to deform permanently to relieve stresses. Strains take place due to extended levels of stress; this stress is less than the rupture stress. In this matter it was chosen a numeric tool to simulate the behavior of salt drilling and the effects that this will have due to the overburden stress and drilling fluid pressure. This tool is Abaqus a program of finite elements in 3D (three dimensions). The objective of this work is to determine the effect of the fluency (creep) in salt during and after the drilling of the well, through numeric simulation. At first it is shown a validation of Abaqus finite element program comparing results from literature and then it is shown a simulation of a 3D vertical salt wellbore.

Keywords: Creep, Drilling, Geomechanics, Evaporites and Wellbore.

1. Introduction

Among offshore basins of Brazil, Campos and Santos basins located Southeast of Brazil, nowadays, are receiving considerable attention from the petroleum industry due to the great results of exploration and production of hydrocarbons. Campos basin is responsible for more than 80% of Brazil's oil production and Santos basin has enormous growth perspectives due to the discovery of new light crude oil. Not long ago, Petrobras confirmed the discovery of light crude oil of 30° API in Santos Basin; finding a reservoir of high productivity, located below a salt layer of two

thousand meters of thickness ("pre-salt") 2,000 m (6561,7 ft). The presence of saline structures in these basins forms favorable conditions to seal petroleum fluids, increasing the success and probability in oil and gas exploration. In this context, evaporite rock is a caprock because it doesn't allow fluids to flow through it, presenting very low permeability. On the other hand, many operational problems in drilling salt structures have been brought up to light, some of the most common problems registered by the petroleum industry are stuck pipe due to salt pinch and wellbore collapse due to inadequate drilling fluid design. Besides these important remarks, the strains of sediments adjacent to salt structures, combined with the stresses of disturbances caused by the presence of salt usually brings a risk in drilling, forming a transition zone where the principal characteristic is the instability of the well and problems of lost circulation. These problems create great challenges and generate the opportunity of evolution in the oil industry. In this way we can say that the complexity of saline bodies and the deep reservoirs request not only high development costs, but also an innovative technology to reach the production fields, being necessary the use of special procedures for drilling through evaporites. An example of this particularity was studied by Willson & Fredrich (2005), Fredrich et al. (2003), Poiate Jr. et al. (2006) and others. These authors presented and showed how these uncertainties close and through salt can be included in the geomechanical project of the well and in the weight of the necessary drilling fluid. The objective of this work is to determine the effect of creep in salt during and after the drilling of the well, this is done by analyzing the behavior of salt creep in a salt well with and without the interaction of weight of the drilling fluid. This evaluation is made through numeric simulation by a finite element commercial program.

1.1 Evaporites in Brazil

Evaporites are sedimentary rocks that present saline minerals layers, being the principal component halite. These are deposited directly of brines in conditions of strong evaporation and precipitation of sedimentary, restricted, hot and subsidence basins. Those deposits could be of continental or marine origin; where there is a periodic contribution. The formation of evaporites are due to trapped lagoons in tropical climates with strong and continuous evaporation, along with systematic or intermittent affluence of salt seawater and with little or any contribution of clastic sediments. The precipitation of salt happens when the solute reaches the point of saline saturation of the respective component. The deposition of saline layers take place as a sequence or succession of progressive salinization of the deposition of the basin. The order of deposition is from less soluble salts to the most soluble salts; for instance, gypsum and anhydrite in lower layers, and halite, silvite and carnalite in higher layers. Evaporites are found in several hydrocarbon basins around of the world. Oliveira et al. (1985) presented a geological study, including aspects of evaporites mainly in Campos Basin. According to this work, the formation of evaporitos in Brazil took place about 135 million years ago, in other words, in the Lower Cretaceous. The process of continental separation created gulfs, previous to total separation (open sea), all over the coast. This propitiated favorable conditions of restriction of seawater flow. All of this process associated to environmental conditions such as dry and hot weather, airing, evaporation, feedings of water source and morphologic restriction were favorable to the formation of evaporite deposits in the Brazilian coast. According to a proposed model, the vertical ascension of salt bodies called halokinesis, has its origin in local salt deposits in each of the corresponding "lagoons" along the basin. This phenomenon is the salt penetration through upper layers of dense rock producing domic structures. As a result of continental separation, the condition of the

environment stopped being restricted, provoking the deposits of sediments in open sea. Santos and Campos basins are complex examples of saline structures. The seismic stratigraphic interpretation and tectonics in these areas are well understood, this is a result of decades of exploration. These sedimentary basins were studied by Chang et al. (1992), they were formed in the Mesozoic era. Marlim field in Campos Basin, for instance, is a field of gigantic oil reserves where originally had a volume of approximately 10 billion bbls of oil, becoming the largest offshore oilfield known in the world. The study of diapiric structures in saline rocks is very important because evaporites are important seals for petroleum fluids, they are excellent caprocks. On the other hand, structures in proximity to salt diapirs are complex. This is because the penetration of salt bodies (halokinesis) causes the deformation of upper layers of dense rocks. The consequence of this is the formation of intense shear around the salt dome, fractured areas and failure zones on the top of the salt dome. These are some of the factors that complicate the drilling of salt surrounding areas.

2. Numerical modeling

2.1 Creep Model of the Finite Element commercial program

The creep model presented and used in the finite element commercial program follows the time hardening form of the Power-law creep model. The time hardening form according to the commercial program has the following equation:

$$\dot{\epsilon}^{cr} = A \cdot q^n \cdot t^m \quad \text{Equation 1}$$

Where $\dot{\epsilon}^{cr}$ is the uniaxial equivalent creep strain rate, q is the uniaxial equivalent deviatoric stress (Mises equivalent stress), t is the total time, and A , n and m are parameters defined by the user as functions of temperature. In order to simulate creep on the commercial program, elastic parameters must be introduced E (Young's modulus) and ν (poisson's ratio). This is because it is considered that an element that has a creep behavior must also have an elastic behavior. It is not in the interest of this paper to discuss the several creep models found in the literature. Although it is important to remark that the time hardening form of the Power law creep model suits well for these simulations.

2.2 Validation of the commercial finite element program

In order to validate further results, it is necessary to match known literature results in the the finite element program. The first validation was made through Bradley's formulation for a circular wellbore, analyzing the elastic response of the well. The second validation was the 3D response of the program by obtaining similar results of Fredrich et al. (2003) experiences in determining 3D in-situ stress in salt bodies. For the first validation, the case of study is the drilling of an oil well of 0,216 m (8½") of diameter in a section in two dimensions (2D), located in the salt layer. This section has the particularity to represent a quarter of the wellbore. The quarter of the wellbore has the purpose of reducing the mesh and computer costs, see Figure 1. The depth of study is 2700 m (8858,3 ft) below the sea level.

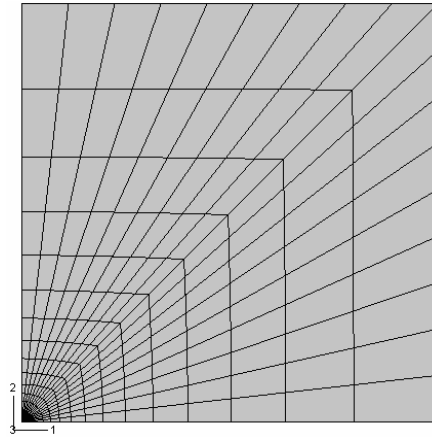


Figure 1. Finite Element 2D mesh.

The equations 2 and 3 formulated by Bradley (1979) for a circular wellbore are:

$$\sigma_r = \left(\frac{\sigma_x + \sigma_y}{2} \right) \left(1 - \frac{a^2}{r^2} \right) + \left(\frac{\sigma_x - \sigma_y}{2} \right) \left(1 + \frac{3a^4}{r^4} - \frac{4a^2}{r^2} \right) \cos 2\theta + \tau_{xy} \left(1 + \frac{3a^4}{r^4} - \frac{4a^2}{r^2} \right) \sin 2\theta + p_w \frac{a^2}{r^2} \quad \text{Equation 2}$$

$$\sigma_\theta = \left(\frac{\sigma_x + \sigma_y}{2} \right) \left(1 + \frac{a^2}{r^2} \right) - \left(\frac{\sigma_x - \sigma_y}{2} \right) \left(1 + \frac{3a^4}{r^4} \right) \cos 2\theta - \tau_{xy} \left(1 + \frac{3a^4}{r^4} \right) \sin 2\theta - p_w \frac{a^2}{r^2} \quad \text{Equation 3}$$

Where σ_r is the normal radial stress, σ_x is the in-situ stress in the x axis, σ_y is the in-situ stress in the y axis, a is the radius of the wellbore, r is the distance from the the center of the wellbore to the specified element, θ = is the angle measured counterclockwise from x axis of plane x-y, σ_θ is the tangential stress and p_w is the pressure due to the drilling fluid.

The principal characteristics of the case of study are presented in Table 1:

Table 1. Principal characteristics of the 2D validation case.

Material	Density	Depth
Sea water	1027 kg/m ³ (64,11 lb/ft ³)	0 m to -500 m (0 ft to -1640,4 ft)
Other sediments	1 psi/ft = 2306,66 kg/m ³ (144 lb/ft ³)	-500 m to -2500 m (-1640,4 ft to -8202,1 ft)
Salt layer	2160 kg/m ³ (134,84 lb/ft ³)	-2500 m to -3000 m (-8202,1 ft to -9842,52 ft)

In order to transfer the total pressure to the studied section located at 2700 m (8858,27 ft) below the sea level (-2700 m), it is necessary to separate the stresses generated by the three areas (sea water, other sediments and the salt layer itself). The first area called “sea water” represents the pressure caused by the weight of the ocean. The area named “other sediments” stands for the rock layers situated above the salt, these layers have a density of 2306,66 kg/m³ (1 psi/ft), this value is accepted as an ideal gradient to simulate the overload of rock formation in the petroleum industry. Finally the salt layer, which represents the salt rock. In this case it was chosen that Halite would represent best the salt layer. Halite is a component of the salt rock and its density is 2160 kg/m³ (134,84 lb/ft³), Medeiros (1999). These formulations were used for the plane strain case. In this simulation the program used only the elastic step. The finite elements analyzed are those found in the lower part of Figure 1 along axis 1. In order to study the behavior of the salt well this study was analyzed under plane strain case, the mesh was built in 2D. The stresses and the displacements in the wellbore were analyzed considering the use of the drilling fluid and not considering it. The salt layer was modeled considering the creep behavior before explained. The general explanation of the numerical simulation procedure is as follows. To simulate the creep behavior of the salt well, a mesh of finite elements was built in 2D. This mesh has the main characteristic of one quarter of the total dimensions of the wellbore, the size of the mesh is of 20 times the radius, as the radius is 0,108 m (4 ¼”), 20*r, this would be 2,16 m (7,09 ft), the dimensions of the mesh are of 2,16 m * 2,16 m. It has 234 plane strain elements (CPE4) and 248 nodes. The characteristic of plane strain elements is that they assume that the out of plane strain is zero. These elements were used in this simulation because they match the 2D criteria of a section wellbore in assuming that the out of plane strains are zero. The reason for which it was adopted 20 times the radius is that in this distance the stresses are equal to in-situ stresses, this fact was verified through previous simulations in the commercial finite element program, and after taking this consideration this mesh size was adopted. In figure 1 the 2D finite element mesh is shown for the simulation of the drilling of the well and in Figure 2 it is shown a zoom of Figure 1, this with the objective of showing the type of elements that were used in the simulation.

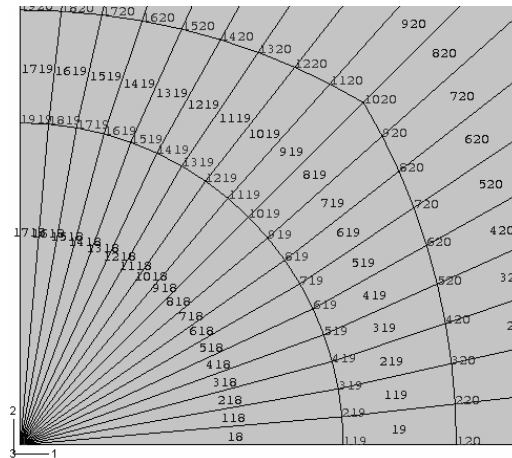


Figure 2. Zoom of the 2D mesh.

From Figures 1 and 2, it can be seen that there are two types of finite elements used to simulate the salt layer, explicitly the wellbore and the rest of the salt rock. In the circle area, in other words, the quarter of the well from the center of the well to the perimeter of the well (see Figure 2) triangular finite elements of 3 nodes were used and in the rest of the mesh quadrilateral finite elements of 4 nodes were used. Once again the analysis as quoted before is set by the plane strain method. The axes represented by the numbers 1, 2 and 3 correspond to x, y and z axes. The nodes located at the vertical left end of figure 1 and the nodes located at the bottom of figure 1 are set to no displacements at all, simulating that it is the continuity of wellbore. After simulating the response of the wellbore due to drilling, it has been found that the results proposed by Bradley (1979) coincide with the results of the commercial program (see Figure 3). In Figure 3 there is a graphic, showing the response for radial stresses and tangential stresses along the elements, these have almost the same values. For the second validation it was chosen the work done by Frederich et al. (2003) obtaining similar results in determining 3D in-situ stress in salt bodies.

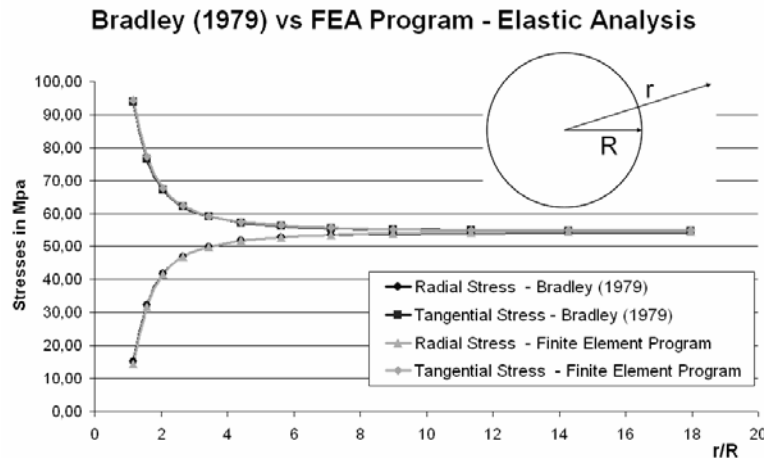


Figure 3. Elastic analysis of Bradley's formulations vs Abaqus Finite Element Program.

Several body shapes were simulated and the same results were found. One example of this is the simulation of a 2000 m (6561,7 ft) salt sphere at 4000 m (13123,3 ft) of depth (top of the sphere). This example was using a mesh of 4625 nodes and 24119 4-node continuum elements. The stress distribution of the numerical simulation of the salt sphere for the von Mises stress, the vertical and horizontal stress agrees with the results presented by Frederich et al. (2003), see Figure 4, 5 and 6.

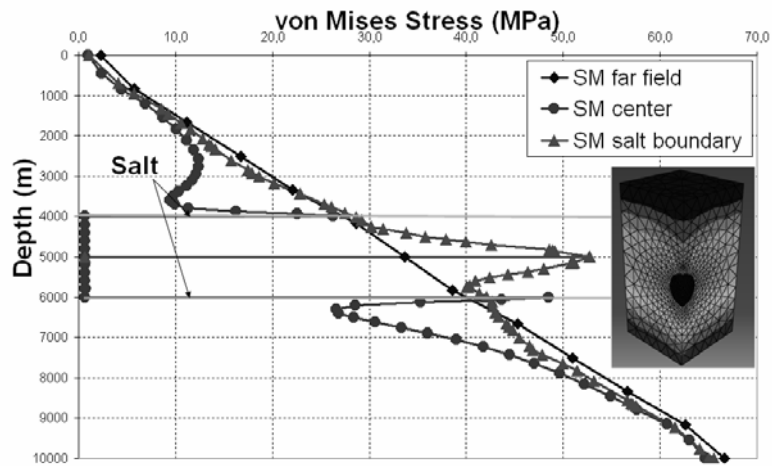


Figure 4. Validation of the 3D capability of Abaqus. Von Misses stresses of a salt sphere. Similar results (Frederich, 2003).

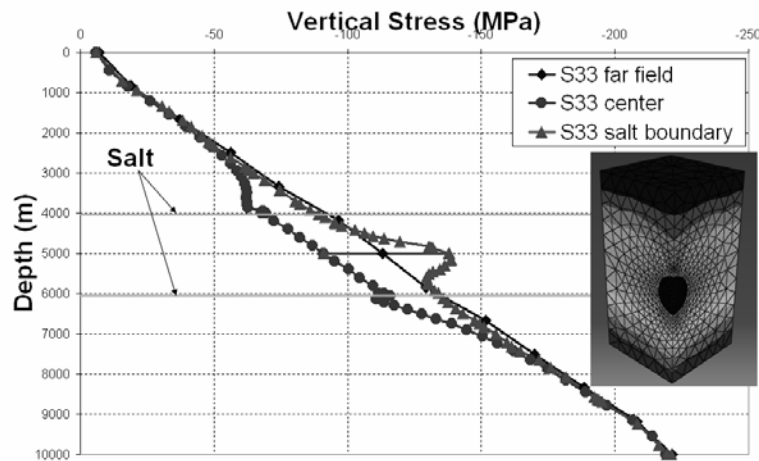


Figure 5. Validation of the 3D capability of Abaqus. Vertical stress of a salt sphere. Similar results (Frederich, 2003).

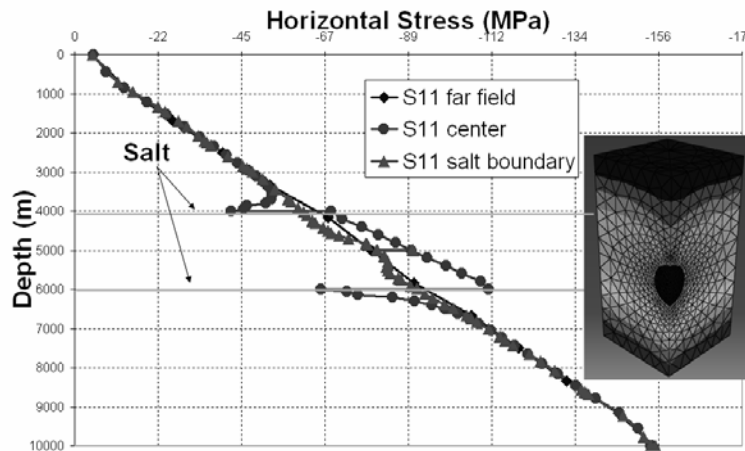


Figure 6. Validation of the 3D capability of Abaqus. Horizontal stress of a salt sphere. Similar results (Frederich, 2003).

3. Cases of study

3.1 2D salt well, creep simulation

After validating the finite element program, new experiences using the program can be accomplished. Using the same input values for the 2D validation case, plane strain case, the following results were obtained; see figure 7 and figure 8.

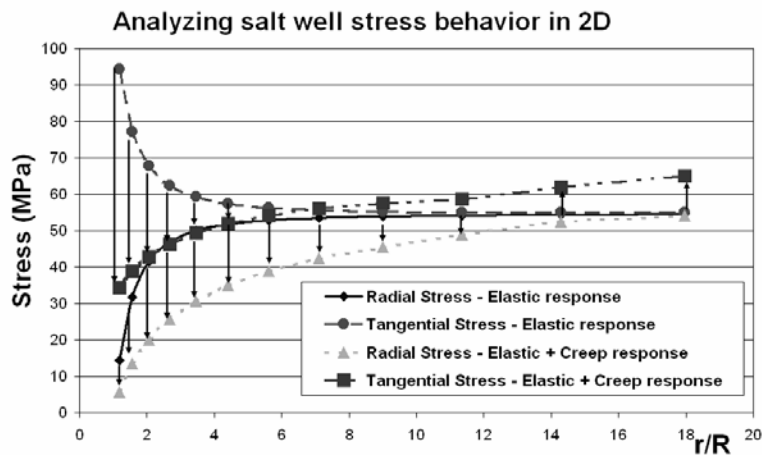


Figure 7. 2D salt well creep stress behavior.

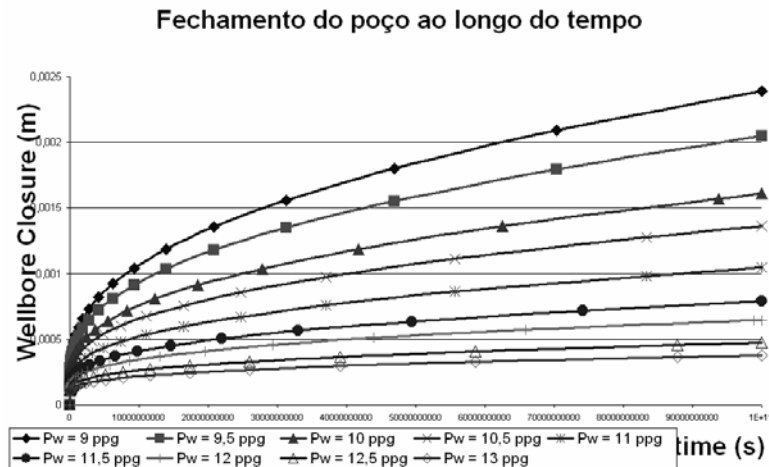


Figure 8. 2D salt well creep behavior for different drilling fluid weights.

Figure 7 presents the analysis of the 2D salt well stress behavior studying the effect of creep. This simulation uses the creep step of the program. This means that three steps are used in this simulation: step 1, introduces the in-situ stresses, step 2 is the elastic response after drilling, and step 3, shows the creep behavior of the salt well. The elements analyzed in Figure 7 are those located at the bottom of Figure 1 along axis 1. These elements have the characteristic that the integration points are located near the center of each element, forming $2,5^\circ$ with axis 1. The values of stresses were obtained through each of these integration points. Also in figure 7, it is shown the elastic response and the creep response of the salt well after the drilling of the wellbore. It is important to notice that in this simulation, the pressure of drilling fluid wasn't taking into account, this is because it was important to understand how the stresses vary through time in a wellbore with no drilling fluid. Other results taking account of the drilling fluid were analyzed also, but are not shown here, this for the sake of showing the most interesting results, although this is not the real life case. The elastic response of the salt wellbore is the response of the wellbore immediately after the well has been drilled, this response is shown through several values of stress of the elements located along axis 1 (elements located in the first row of the bottom of Figure 1). In figure 7 it is shown curves of the radial and tangential stress of these elements. After the elastic response, follows the creep response shown as "Elastic + Creep response" this step shows how stresses have changed after time passed, arrows show the trajectory of stresses through time for each element. Only for the purpose of an academic study the final creep time was set to $10E11$ seconds. Analyzing the tangential stress curves only, it is possible to see that up to a distance of approximately 5 times the radius $5 \cdot R$ (distance from the center of the wellbore) the values of the tangential stress stop decreasing, and from there on they increase in their values through time. Another interesting fact is that the radial stresses decrease their values through time in all the studied elements, until $20 \cdot R$ which is the distance where stresses stabilize, e.g. are equal to field stresses. In figure 8 it is shown the graphic of the wellbore closure through time for different values of the drilling fluid pressure, these values vary from 9 ppg (0,47 psi/ft) to 13 ppg (0,67

psi/ft). In the numerical simulation this fluid pressure is taking into account as non-penetrating only analyzing the geomechanical response of the wellbore. In this figure the node of study is node No. 119 (see Figure 2). This node is located at the edge of the wellbore. It is seen from figure 8 that different weights of drilling fluid have different response on the wellbore closure. At the end, a lower drilling fluid weight provokes a higher wellbore closure.

3.2 3D vertical salt well drilling simulation

In order to simulate the drilling of a 3D vertical salt wellbore a mesh of 2460 nodes and 1880 8-node hexahedral elements with reduced integration (C3D8R) was created. This mesh can be seen in Figure 9. Note that the elements in the center are the elements that will simulate the wellbore.

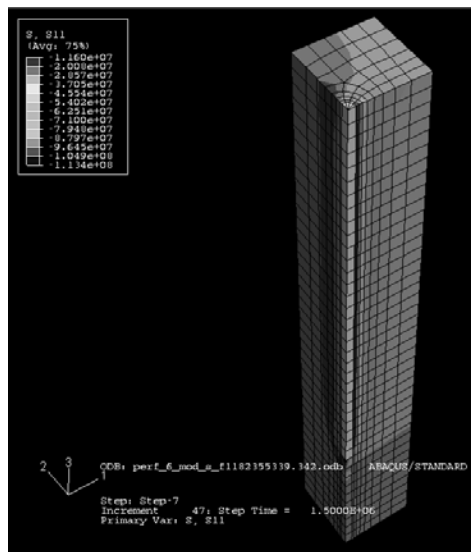


Figure 9. Finite Element mesh for the 3D vertical salt wellbore drilling simulation.

The purpose of this mesh is to represent the drilling of 14 m of a salt wellbore located at 4000 m (13123,3 ft) deep. The simulation of the drilling was divided in 4 stages of 3,5 m (11,5 ft) (see Figure 10). In figure 10, 0 m represents the top of the mesh this point has 4000 m (13123,3 ft) of depth, 3,5 m (11,5 ft) represents 4003,5 m (13131,48 ft) and so on. Node No. 18 has 4003,5 m (13131,48 ft) of depth and node No. 9 has 4010,5 m (13154,44 ft) of depth. Nodes No. 18 and 9 will be studied further on.

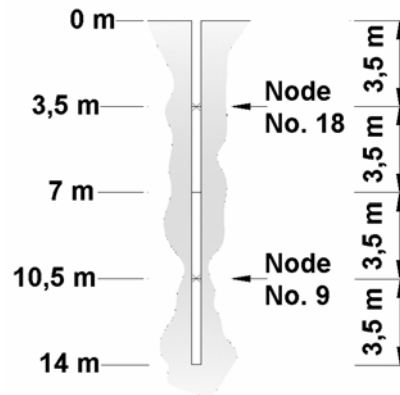


Figure 10. Description of the 3D vertical salt well.

The overburden weight passed at the top of the mesh, represents the weight of the rock mass, this overburden was calculated using the 1 psi/ft gradient. The total stress at the top of the mesh would be 90520000 Pa (13128,82 psi) similar procedure was adopted to pass the stresses to the sideburden of the mesh (in Figure 9, these sides are the ones located at the back), this also taking into account that the horizontal to vertical ratio of stress is 1. The drilling fluid weight is 11 ppg (0,57 psi/ft), that produces a pressure of 51720000 Pa (7501,35 psi = 51,7 MPa). Three steps were used to simulate the drilling, 1 the in-situ stresses, 2 the elastic response of the wellbore after being drilled and the immediate pressure of the drilling fluid to the faces of the wellbore and finally 3 the creep response of the salt mass. Steps number 2 and 3 were used to simulate the rest of the drilling stages. Figures 11 and 12 show the results of the wellbore closure analyzing the presence of drilling fluid and not. Both figures 11 and 12 study the reponse of nodes 18 and 9. Figure 11 shows the response of wellbore closure vs the depth of penetration. Figure 12 represents the results of wellbore closure through time (in hours). From these two figures analyzing only the behavior of node No. 18 it seen that the elastic response begins when the drill bit reaches this depth this elastic response is immediately, after the creep behavior starts to come in evidence.

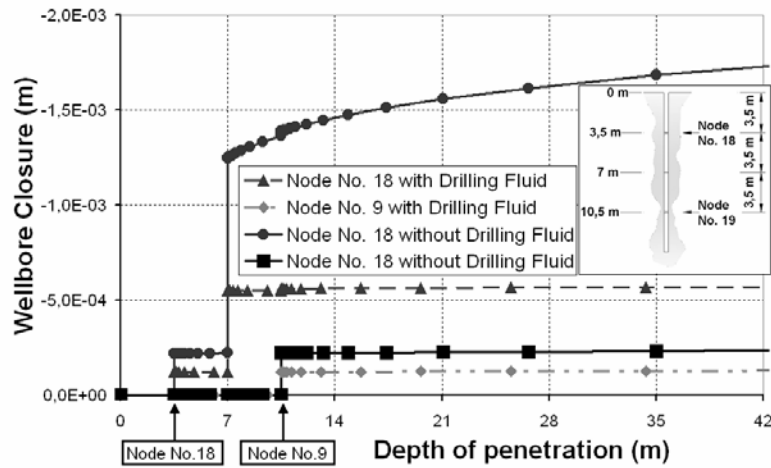


Figure 11. 3D salt well, elastic + creep behavior for nodes No. 18 and 9. Notice the elastic behavior first and then the creep behavior.

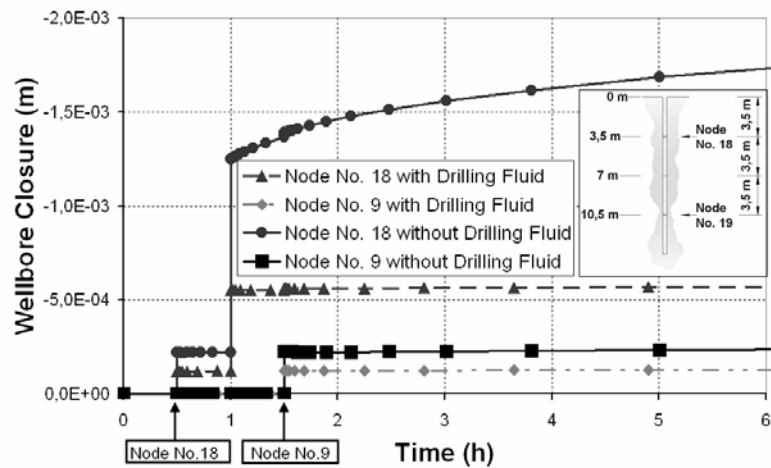


Figure 12. 3D vertical salt well, elastic + creep behavior for nodes No. 18 and 9. Analyzing wellbore closure vs time.

Figure 13 and 14 shows the stress response of the vertical 3D drilling simulation of a salt well considering the creep behavior. In Figure 13 it is shown a red line, this line marks the elements which are analyzed. Figure 14 includes the radial and tangential stress response; this figure is similar to Figure 7. Comparing Figure 7 and figure 14 it is seen that radial and tangential demonstrate the same behavior in their trajectories through time.

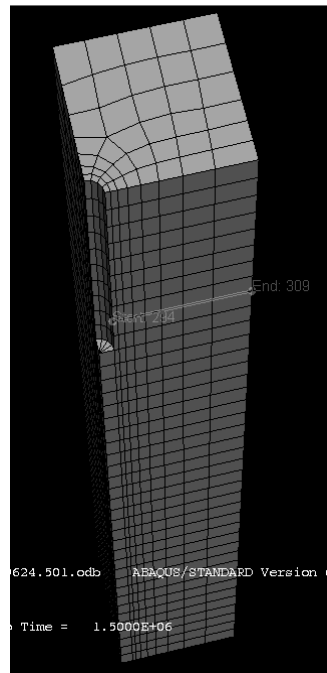


Figure 13. Finite Element mesh for the 3D vertical salt wellbore drilling simulation. Elements marked in red are analyzed in Figure 14.

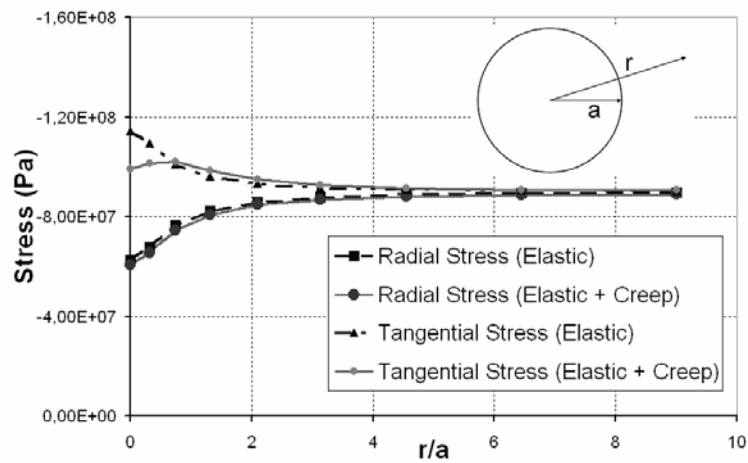


Figure 14. 3D salt well creep behavior response of radial and tangential stresses.

4. Conclusions

The time hardening form is the simplest form of the power law model and it has been demonstrated that it suits well to develop the results of the salt wellbore drilling simulation.

The A, n and m parameters of the time hardening power law presented will vary depending on the depth (earth pressure - overburden) and temperature (temperature gradient). In this paper the parameters were calibrated from Costa et al. (2005).

Through the validations it was possible to acknowledge that the finite element commercial program can reproduce accurate results.

In the numerical simulations presented in this paper, 2D and 3D results were obtained regarding mainly the wellbore closure and the induced stresses caused after the drilling. Then it was possible to state that the cause of a rapid wellbore closure is a low weight of drilling fluid. This is an essential data to know what will be the specific time lapse of the casing, before the well suffers a complete salt pinch, it is also important to prevent stuck pipe. Another interesting response is the trajectories of stresses through time. These trajectories at some point stabilize, this depends if they are tangential or radial stresses. Tangential stresses decrease their values through time in up to five times the radius and then they increase their values. Radial stresses decrease their values through time in all the radial extension up to almost 16 times the radius. At a length of 20 times the radius (or before), starting from the center of the wellbore, they behave like the continuum medium (equal to the far field stress).

These results present an initial stage of the research of salt-evaporites behavior. In further research works the objective is to determine how parameters such as depth, temperature, evaporite type and others influence results.

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