Local remesh procedure to model reaming in vertical oil wells drilled through salt rocks

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Abstract. This paper presents an alternative methodology, based on cutting and adjusting finite elements, to model reaming and reamer passage in salt rocks during vertical wells drilling. The developed strategy ensures that the stress, deformation, and displacement fields are maintained after the remesh. To reach the pre-salt hydrocarbon reservoirs it is necessary to pass through thick layers of salt rocks. The mobility of these salt rocks can cause serious operational problems, such as the imprisonment of the drill string, casing collapse and annular entrapment of columns, compromising the casing integrity. Therefore, adequate monitoring of the well diameter must be done constantly throughout the entire drilling process. Thus, reaming procedures may be required to recondition the diameter of the well to its original state. The reconditioning diameter procedure is sometimes achieved by using reamers, which are cutting tools used for enlarging and finishing the diameter of a pre-drilled hole to a precise size. The reamer passage during drilling operation in saline rocks will be also considered herein. The reconditioning strategy presented in this work is based on removing and adjusting mesh elements reestablishing the initial radius of the well in specific regions. This procedure improves the precision and realism of the simulations, avoiding the appearance of a gap between the mesh and drill bit passage. Regarding the reamer passage, the removal and adjustment of elements will be considered concomitantly with the reamer advancement. Stress graphs along the wellbore and comparisons with real wells data are used to enhance the phenomena understanding and validate the proposed methodology.

Keywords: Salt Rocks; Local Remesh; Finite Element Method.

1 Introduction

The saline rocks mobility can cause problems, such as column entrapment, high torque, casing collapse and annulus closure, causing enormous losses in several areas. The drilling fluid weight can causes hydrostatic pressure that serves as counter pressure to the salt's displacement. However, sometimes this is not sufficient, leading to the need to incorporate it via computational tools during the drilling operation in saline rocks [1].

In reaming operations, it is ensured that the well diameter returns to that predicted in the project (initial diameter) for the continuation of other well conditioning operations. Taking into account the mobility of saline rocks, this operation becomes frequent and strategic, in order to avoid serious operational problems. Then, adequate monitoring of the well diameter must be carried out constantly throughout the entire drilling process. The procedure of reconditioning diameter can be achieved using reamers, which are cutting tools used for enlarging and finishing the diameter of a pre-drilled hole to a precise size. The main function of the reamer in enlarge the borehole to the desirable size during drilling in saline rocks. In such case, as in other reconditioning operations, the salt layer must be moved and adjusted allowing the reamer passage.

According to Yarim et al.[2], there are several situations in which the diameter of the well must be reconfigured: problems during the column removal procedure; conditioning the well diameter for installation of casings; elimination of sections with very small diameters, correction of the advancement of highly mobile formations, and removal of cuttings along the well diameter in horizontal wells.

Operational problems related to drill string trapping occur when the well walls move too much, to the point of touching the string equipment. During the drilling process in rocks with high mobility, the objective is that the gap between the drilled diameter and the equipment diameters is not overcome by displacements. Then, a security limit is considered for which the reaming is trigger[3].

Despite contributing to the adequate conditioning of the well diameter, this procedure should not be carried out in some situations[4]. The indiscriminate practice of this methodology can cause the opposite effect to that desired, contributing to the collapse of the well in poorly consolidated regions, such as fractured layers. This type of rock is sensitive to the mechanical agitation of the drill string, which can generate the accumulation of cuttings that make it difficult to effectively clean the open well. Further, the lack of contact between the drill bit and the well bottom increases the mechanical instability of the column, which can collide with the formations[5].

In this work, We propose an alternative local remeshing procedure to model reaming and reamer passage during vertical wells drilling. The methodology is based on cutting and adjusting finite elements reestablishing the initial radius of the well in specific regions. In the case of reamer representation, the removal and adjustment of elements will be considered concomitantly with the reamer advancement. Stress and displacement graphs along the wellbore and comparisons with real wells data are used to enhance the phenomena understanding and validate the proposed methodology.

2 Local Remeshing Procedure: Reaming Representation

The usual reaming strategy implemented consists of removing (deactivating) the mesh elements that are between the limit radius and the initial radius (drill bit diameter), reestablishing the initial radius of the well in that region[1]. As an alternative to this methodology, a new reaming methodology is used, consisting of the shortening (adjustment) of the last element between the initial and the critical radius. In the previous methodology, this element would be deactivated, which would generate a region with a diameter larger than that of the drill, which does not match what actually happens in the field. Thus, the adjustment of the elements allows an improvement in accuracy during the simulation, avoiding the appearance of a difference between the diameter of the passed mesh and that of the drill (gap)[6]. In the usual reaming approach, the gap is attenuated by using a finer mesh in this region, which increases the computational costs. On the opposite, the alternative methodology proposed here does not require a fine mesh, since the element adjustment enables the gap disappearance.

Figure1 describes the difference between the diameter of the mesh and the drill bit (gap error) during the well drilling process. The last picture in Fig.1 presents the alternative methodology used, which consists of shortening the last element between the critical and initial radius (drill bit diameter). This new methodology eliminates the gap, improving precision during the simulation. Besides, it is important to highlight that the use of the reaming methodology without adjusting the elements requires greater refinement close to the well radius, since smaller elements are necessary to guarantee smaller gaps. It is worth mentioning that this greater refinement is not due to the accuracy of the result, it is just a way of reducing the gap. The introduction of the adjustment methodology makes it possible to use less refined meshes, by eliminating the gap.

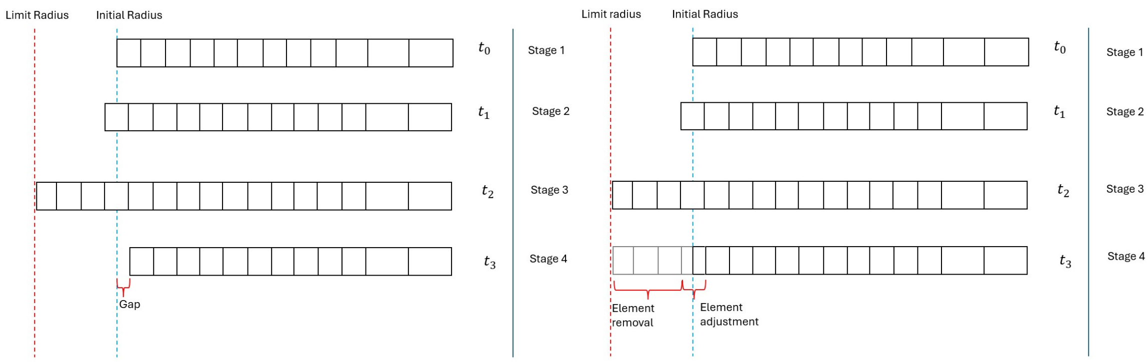

Figure 1. Gap between the initial radius and the first node after reaming (left picture) and the element adjustment (right picture)

At each instant of time, it is checked if the elements nodes exceed the limit radius. In the positive case, a new remesh procedure can be carried out, following the methodology proposed here. The consistency of the solution is guaranteed by the reconditioning of the matrices and vectors involved in displacements calculation, since the deactivated nodes no longer contribute to the mesh. Finally, the adjusted elements have their influence on the modified global stiffness matrix, once the adjustment of the element modifies its stiffness.

3 Local Remeshing Procedure: Reamer Representation

As mentioned before, the reamer is a widely used tool to enlarge the borehole of the well to the desirable size during drilling in saline rocks. In some cases, the well diameter reconfiguration may be to the original size of the drill bit. In such case, the reamer is often referred as a well's stabiliser. Due to such importance in wells drilling procedures, the reamer passage will be here considered, and the same strategy used in the reaming representation, will be also used. However, herein, the removal and adjustment of elements will be considered concomitantly with the reamer advancement.

4 Displacement mapping

In the problem under analysis, λ represents a vector quantity evaluated in the domain of the element. Thus, the fields of this quantity can be calculated using the interpolation functions (N_i) for each node. As isoparametric elements are used, the same shape functions (N_i) interpolate displacements and nodal coordinates, mapping these parameters within each finite element. This mapping is done according to the equation below:

$$\lambda(\xi) = \sum_i N_i(\xi)\lambda_i \tag{1}$$

where λ_i is the value of the parameter at node i.

Figure 2 introduces the proposed strategy for readjusting the element's nodes. The strategy consists of an initial stage, where the need to adjust the element is verified if it is being cut by the well radius (x_r). The second step consists of making the adjustment based on this radius (x_r). The deformed (x_i) and undeformed (X_i) positions are related as follows:

$$x_i = X_i + u_i \tag{2}$$

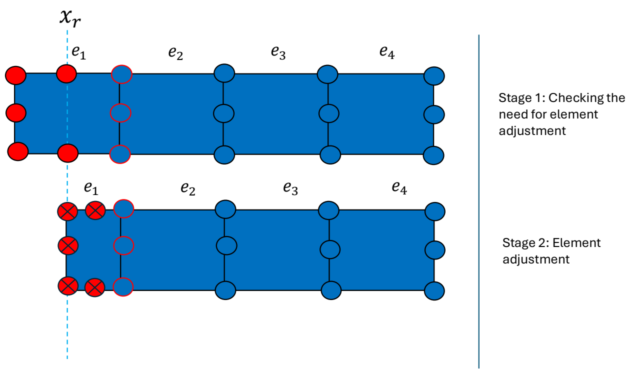

Figure 2. Steps for adjusting the last element

Based on eq.(1), it is possible to redefine the element, considering the position of the nodes to the left of the element to be shortened (adjusted). Therefore, it is necessary to map the coordinates and displacements and calculate the parametric coordinate on the cutting line (x_r), referring to the element to be shortened (e_1). This is done using the equation below:

$$x_r = \sum_i N_i(\xi_r)x_i \tag{3}$$

The positions of the intermediate nodes of the adjusted elements are defined based on the new position of the nodes on the left and the position of the nodes on the right that are unchanged. Thus, the nodal representation of the adjusted element is completed.

5 Strain mapping

It is important to mention that many of the integrals used in Finite Element Method (FEM) are not trivial, which makes necessary to use numerical integration techniques, such as Gauss integration. When using this type of integration, information related to the stress and deformation of the elements is calculated at the integration points, called Gauss points. With the evolution of viscous deformation over time, this information is stored and is increased throughout the simulation. Then, when the finite element is redefined, it is also necessary to map its viscous deformations to the new parameter space, and find their values in the new positions of the element's integration points. For this purpose, polynomial interpolations are used, taking into account the number of Gauss points of the adjusted element. The stress values acting at the element's integration points are calculated at each time step based on its total and viscous deformation field, and it is not necessary to map it to this field when the element is redefined. Finally, details about the viscoelastic constitutive model, and the FEM formulation used in this work can be found in Sobrinho et al.[1]

6 Results and discussion

After defining the reconition diameter strategy with element adjustment, two scenarios will be proposed to verify this methodology. The first scenario is the simplest one, with only one layer of Halite. The second one, is more complex, and has Halite interspersed with portions of carnallite.

6.1 First application

In the first scenario, the local remesh procedure utilised in this paper will be verified during the reaming procedure. When the salt layer, reaches the limit radius, due to viscous deformations, the reaming procedure starts with the removal and adjustment of the elements to the initial diameter (drill bit diameter). The drill bit radius is 6.125" and the limit radius is 6.0625". Figure 3 presents well geometric properties and the lithology. Regarding the simulation, a total of 2750 (with adjustment) and 5500 (without adjustment) quadratic quadrilateral elements are used. Finally, the drilling duration is 10 hours.

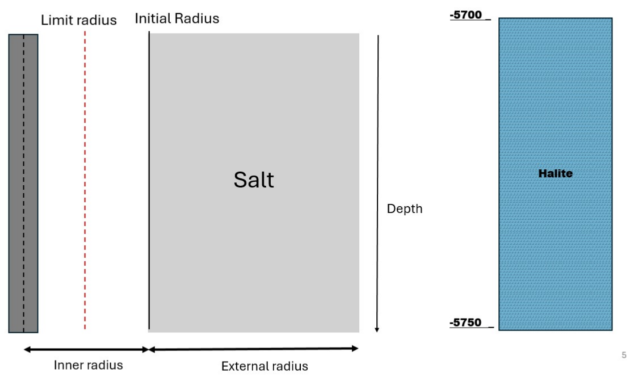

Figure 3. Well geometric properties and lithology (Halite)

In Fig.4, it is possible to evaluate the evolution of the von Mises stress during the drilling. In the figures under analysis, the vertical axis refers to the well depth, while the horizontal, the well radius. A comparative analysis between the two methodologies (without/with local remesh procedure) is performed. It can be observed that the local remesh methodology (column on the left) can satisfactorily represent the stress field. Further, the adjustment of the element enables the use of a finer mesh, since this methodology avoids the appearance of the gap simulation error, Fig.1. Besides, the local remesh procedure utilised in this work enables the well diameter reconfiguration, as the finite elements return to the initial diameter (black line).

Figure 5 presents the displacement field at a node located in the lowest point of the Halite layer (5750 m). As expected, the adjustment methodology causes gap error disappearance, once the element is reconditioned to the initial radius (drill bit radius). Then, this methodology enables the non-requirement of a finer mesh in this region.

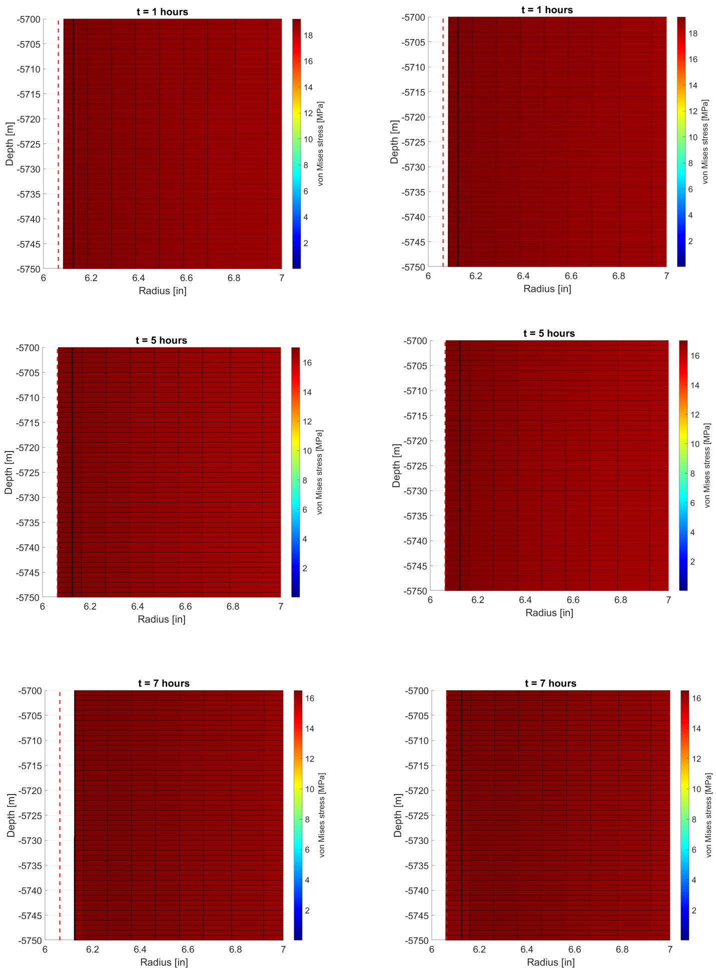

Figure 4. von Mises stress for the methodologies with/without local remesh

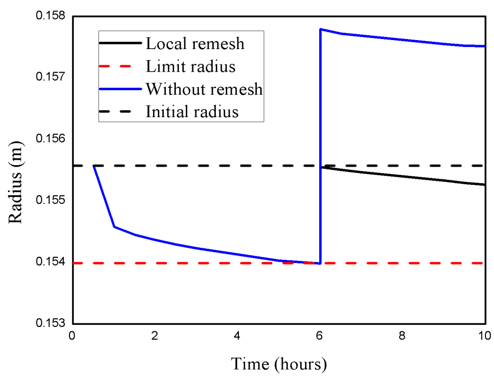

Figure 5. Well displacement field considering the methodology with/without element adjustment (local remesh).

6.2 Second application

In this scenario, the local remesh procedure will be verified in a well with a reamer. When the reamer is activated, the elements around it are removed or adjusted to the reamer diameter. This procedure enables the reamer passage, without modifying the displacement and stresses fields. Figure 6 presents some details of the model used to verify the local remesh methodology used herein. The lithology of the well is based on portions of Halite interspersed with potions of carnallite, Fig.6. Regarding the simulation, a total of 4080 (local remesh) and 8160 (without local remesh) quadratic quadrilateral elements are used. Finally, the drilling duration is 150 hours.

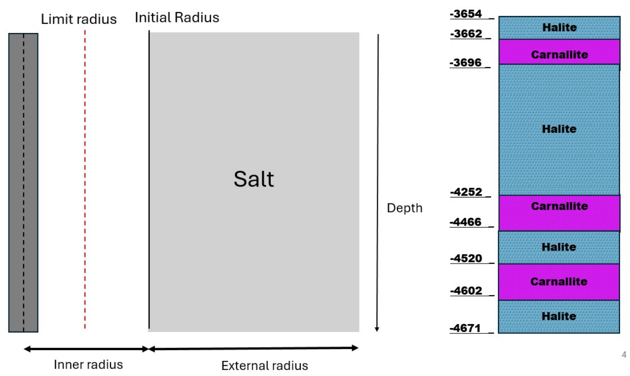

Figure 6. Well geometric properties and lithology (Halite and carnallite)

The drill radius is 6.125” (well radius), while the reamer radius is 6.375”. In Fig.7, it is possible to evaluate the evolution of the von Mises stress during drilling time. In the figures analyzed, the vertical axis represents well depth, while the horizontal axis indicates the well radius. It can be observed that the presence of a reamer is responsible for the redefinition of the elements in this region. In other words, the reamer passage enables the borehole reconfiguration to the reamer radius (blue line). As it can be seen in Fig.7, the methodology with element adjustment can satisfactorily represent the stress field. Further, adjustment of the element enables the use of a less refined mesh, as avoids the appearance of the gap simulation error.

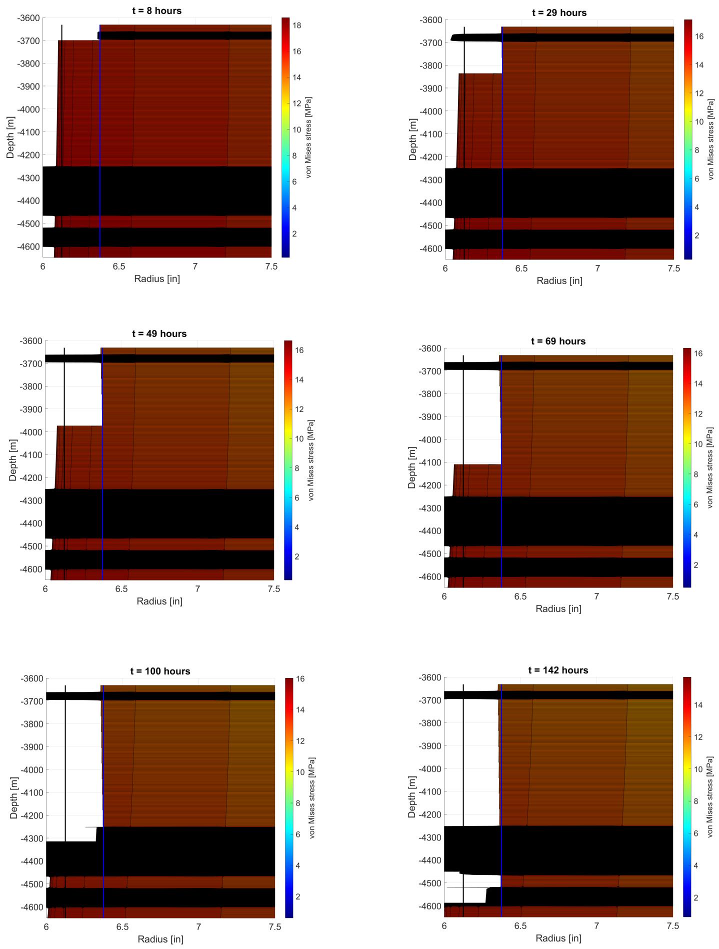

Figure 7. von Mises stress for the methodology considering local remesh

Figure 8 presents the displacement field at a point located in the lowest portion of the Halite layer (4671 m). As expected, the adjustment methodology causes reconfiguration of the well to reamer radius, concomitantly with the reamer passage.

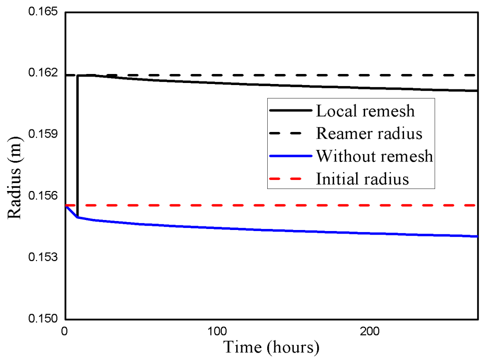

Figure 8. Well displacement field with/without element adjustment (local remesh).

7 Conclusions

This paper presented an alternative methodology, based on cutting and adjusting finite elements, to model reaming and reamer passage in salt rocks during vertical wells drilling. The developed strategy ensures that the stress, deformation, and displacement fields are maintained after the local remesh, according to Figs.6, 7 and 8. This procedure improves the precision and realism of the simulations, avoiding the appearance of a gap between the mesh and drill bit passage. Stress graphs along the wellbore were used to enhance the phenomena understanding and validate the proposed methodology. Finally, the methodology used as capable of representing the reaming operation and also the reamer passage ensuring the stress and displacement fields.

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