

Geomechanical Analysis on Horizontal Wellbore Stability

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Abstract

The drilling, production and injection activities disturb the initial equilibrium in rock formations, causing a change in mechanical conditions and virgin *in situ* stresses. This originates a stress redistribution around the wellbore, which may affect the drilling and completion operations as well as the production efficiency, resulting in increased cost and delay in operations.

This work aims to analyse the behaviour in terms of stress/strain of rock formation around a wellbore, during its production period, as well as to investigate the influence of stress state anisotropy in the determination of wellbore direction in order to assure its stability. For this purpose, two cases of a wellbore at depth of 2625 m were considered, one aligned with the maximum horizontal stress and another with the minimum horizontal stress.

In the problem analysis it was used a set of data from a synthetic oil reservoir. The simulations were done using the finite element code PLAXIS 2D and the Mohr-Coulomb failure criterion. Three cases in the model were simulated, in order to investigate the influence that pore pressure reduction, throughout the production time, in the reservoir in conjunction with different *in situ* stress conditions and different wellbore orientations have in the rock deformation around the wellbore and in its stability.

The results show that principal stresses, mobilized shear stress and deformation are greater in the case of the wellbore be parallel to the minimum horizontal stress. The drilling direction recommended is that aligned to maximum horizontal stress.

Keywords: Geomechanics, Stability, Stress, Strain, Wellbore, Finite Element

1 Introduction

The drilling, production and injection operations affect the initial equilibrium in rock masses, leading to an alteration of mechanical conditions of rock and stress state around the wellbore. This may lead to deviatoric stresses greater than those the rock formation can support, resulting in a failure situation. Such situation causes problems in the drilling and completion operations as well as in the production efficiency, resulting in increased cost and delay in the operations. The knowledge of stresses and strains around a wellbore is essential to evaluate its stability and performance.

Stability problems are situations which are not seldom cases in petroleum industry. It is estimated that stability problems amount to 5-10% of drilling costs in exploration and production, implying a worldwide cost to this industry of million dollars per year (Fjaer *et al.*, 2008).

Hence, it is very important to implement a strategy in order to avoid or minimize geomechanical problems during the development and exploitation period of an oil field. In this strategy, geomechanical analysis takes an essential role.

Several authors has been directed considerable contribution to solve rock mechanics problems associated with wellbore instability through developing and investigating theoretical concepts (Bradley, 1979a, 1979b; Amadei, 1996; Ottosen *et al.*, 1999; Moos *et al.*, 2003; McIntosh, 2004; Zeynali, 2012), implementing new analytical solutions and prediction methods (Aadnøy, 1988; Aoki *et al.*, 1993; Ong and Roegiers, 1993; Liang, 2002; Al-Ajmi and Zimmerman, 2009; Lee *et al.*, 2012; Yuan *et al.*, 2012; Zhang, 2012), understanding and investigating fracture reactivation mechanism in fractured formations (Younessi and Rasouli, 2010), establishing wellbore stability analyses based on non-continuum mechanics (Zhang *et al.*, 1999; Chen *et al.*, 2003; Yan *et al.*, 2013; Jamshidi and Amani, 2014) and reporting and applying field experience (Vernick and Zoback, 1990; Mastin *et al.*, 1991; Santarelli, *et al.*, 1992, 1992a; Mohiuddin *et al.*, 2006).

In this paper are present numerical simulations to analyse the stress/strain behaviour of rock formation around a wellbore, during its production period, as well as to investigate the influence of stress state anisotropy in the determination of wellbore direction in order to assure its stability. For this purpose, two cases of a wellbore at depth of 2625 m were considered, one aligned with the maximum horizontal stress and another with the minimum horizontal stress.

2 Methodology

The numerical analysis presented in this paper was carried out using a finite element code, named Plaxis 2D, which is a program specially developed for geomechanical applications.

In the finite element method (FEM) a continuum medium is divided in smaller elements, named finite elements, which maintain the same properties of the original medium. These elements are described by differential equations and are solved through mathematical models. FEM has the advantage to permit analyse materials with elastic-plastic behaviour, as well as analysis in anisotropic medium. Another advantage of this method is the consideration of arbitrary orientations for a wellbore related to the principal stresses (Plaxis bv, 2012).

For additional information on PLAXIS, the reader is referred to the PLAXIS 2D User's Manual.

In order to build the model, it was necessary to specify three fundamental components for the calculations:

- Element finite mesh;
- Constitutive model and material properties;
- Initial conditions and boundary conditions.

The mesh defines the problem geometry. The constitutive model and material properties establish the type of model response, when it is subjected to a perturbation. The initial and boundary conditions define the *in situ* conditions before a change occurs due to a perturbation in the system.

To increase the results accuracy, a refined mesh was built.

In the numerical analysis it was used a linear elastic-plastic model, with a Mohr-Coulomb failure model.

In the design of finite element model it was used a plain strain model and triangular elements with 15-nods.

3 Description and development of simulation model

In this section, it is described the simulation model and referred the basic elements used as the main input data in the model, in order to do the numerical analysis presented in this paper.

3.1 Geometry, properties and boundary conditions

The conceptual model corresponds to a two-dimensional plain strain horizontal square grid normal to the wellbore axis. The wellbore, with diameter 0.216 m (8.5"), is located at the centre of the grid, which dimension is ten times the wellbore diameter, in order to avoid the boundary effects, as illustrated in figure 1.

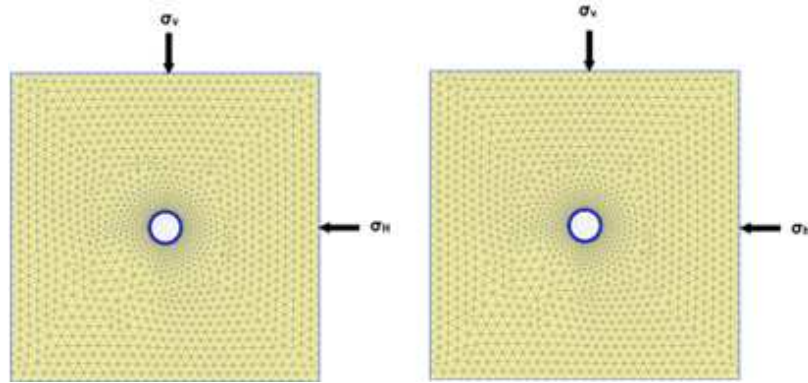


Figure 1 – Conceptual model and boundary conditions.

The problem domain (section corresponding to production liner), at depth of 2625 m, is subjected to an initial pore pressure (P_p) of 37.23 MPa, *in situ* vertical stress (σ_v), major and minor horizontal stresses (σ_H and σ_h), which values are referred to table 1.

Table 1 – Summary of initial stress conditions.

Depth, z (m)	σ_v (MPa)	σ_H (MPa)	σ_h (MPa)
2625	60.90	60.90	45.67
		121.80	

Vertical stress at a specific depth is equal to the weight of overburden. Thus, *in situ* vertical stress can be calculated using the equation 1 (Fjaer *et al.*, 2008):

$$\sigma_v = \int_0^z \rho(z) g dz \quad (1)$$

where σ_v is the vertical stress, $\rho(z)$ is the density as function of depth and g is the acceleration of gravity.

For the Stanford VI reservoir there is no information about horizontal stresses, so that, were assumed for the maximum horizontal stress (σ_H) two cases, corresponding to a magnitude of $2\sigma_v$ and $1\sigma_v$, respectively, and for the minimum horizontal stress (σ_h) a magnitude of $0.75\sigma_v$, taking into account Chen *et al.* (2002), Herget (1988), Tan *et al.* (1993) who say that for typical reservoir depths the ratio σ_H/σ_v varies between 1 and 2 and σ_h/σ_v varies between 0.3 and 1.5. Thus, it was assumed a stress regime consistent with strike-slip/normal fault regime, i.e. $\sigma_H \geq \sigma_v > \sigma_h$.

The rock mass was assumed to undergo linear elastic-plastic deformations with the Mohr-Coulomb failure criterion. The physical and mechanical properties of intact rock used in the model, which represent typical values of the synthetic reservoir Stanford VI (Castro *et al.*, 2005), are given in table 2.

Table 2 – Physical and mechanical parameters of reservoir formations (From: Castro *et al.*, 2005).

Parameter	Shale	Sandstone
Density, ρ (kg/m ³)	2370	2200
Porosity, ϕ (%)	6	26
Permeability, k (m/day)	0.019	2.239
Poisson's ratio, ν	0.35	0.21
Young's modulus, E (GPa)	14.36	9.01
Bulk modulus, K (GPa)	15.67	5.21
Shear modulus, G (GPa)	5.33	3.72
P-wave velocity, V_p (m/s)	3100	2150
S-wave velocity, V_s (m/s)	1500	1300

Due to lack of information about strength parameters – cohesion, friction angle and tensile strength – for the reservoir, these parameters were assumed based on characteristic values for this type of formations, from Goodman, 1980, as shown in table 3.

Table 3 – Strength parameters considered (From: Goodman, 1980).

Parameter	Shale	Sandstone
Friction angle, φ (°)	14.4	27.8
Cohesion, S_0 (MPa)	38.4	27.2
Tensile strength, T_0 (MPa)	-	1.17

3.2 Modelling of stress/strain around the wellbore

In order to assess the stress/strain response of rock mass around the wellbore during the productive period, it was considered the pore pressure reduction in the reservoir, as referred to table 4.

Table 4 – Reservoir pressure history (From: Castro *et al.*, 2005).

Time, t (years)	Pore pressure, Pp (MPa)
0	37.23
10	28.96
20	22.06
30	20.68

Varying the *in situ* stress conditions (corresponding to $\sigma_H/\sigma_v=1$, $\sigma_H/\sigma_v=2$ e $\sigma_H/\sigma_v=0.75$) and taking into account the pore pressure reduction throughout the productive period, three cases in the model were simulated in purpose to investigate the influence that different values of pore pressure in the reservoir in conjunction with each initial stress condition and wellbore orientation have on rock deformation.

To monitor the deformations, it was considered, in each case studied, two groups of points around the wellbore, one, aligned with the direction of vertical stress (points K, L, M, N and O, P, Q, R), and the other, aligned with the direction of horizontal stress (points G, S, T, J). In each group, the distances of each point to the wellbore wall are 0; 0.10; 0.22; 0.50 m, respectively. The monitoring points are illustrated in figure 2.

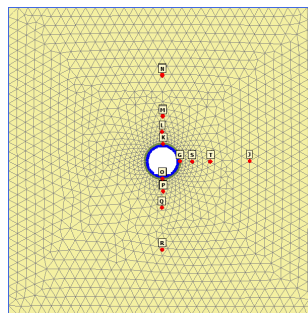


Figure 2 – Monitoring points location.

4 Results and discussion

The stress/strain around the wellbore was analysed for the three cases considered.

The drilling and production operations cause a change in the original stress state of rock formation, with redistribution of stress around the wellbore. This situation leads to a stress concentration and reorientation as illustrated in figure 3, which shows the orientation of the maximum and the minimum principal effective stress in the start of production for the case of the wellbore aligned with the maximum horizontal stress.

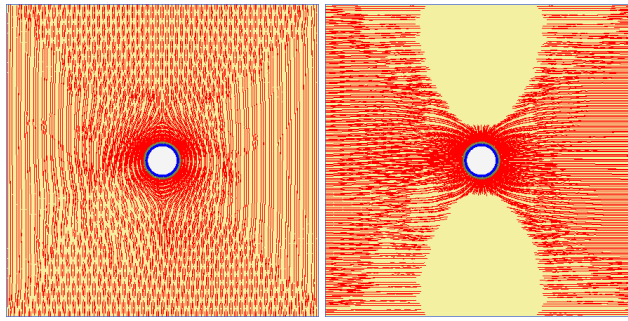


Figure 3 – Direction of maximum (on the left) and minimum (on the right) principal effective stress.

From figure 3, it can be observed a convergence of stress orientation and stress magnitude to the initial stress state as the distance from the wellbore wall increases. From the same figure, it can be stated that the maximum principal stress corresponds to the tangential stress (σ_θ) and the minimum principal stress corresponds to the radial stress (σ_r).

The reservoir depletion also causes a concentration and alteration of stress magnitude around the wellbore. In order to study the evolution of stress magnitude, during the productive period, different productive phases, for each case considered, were simulated.

The stresses distribution around the wellbore, for each case analysed, as function of pore pressure (Pp) variation is shown in figures 4, 5 and 6. In each figure, Pp=37.23 MPa (top left), Pp=28.96 MPa (top right), Pp=22.06 MPa (bottom left) and 20.68 MPa (bottom right).

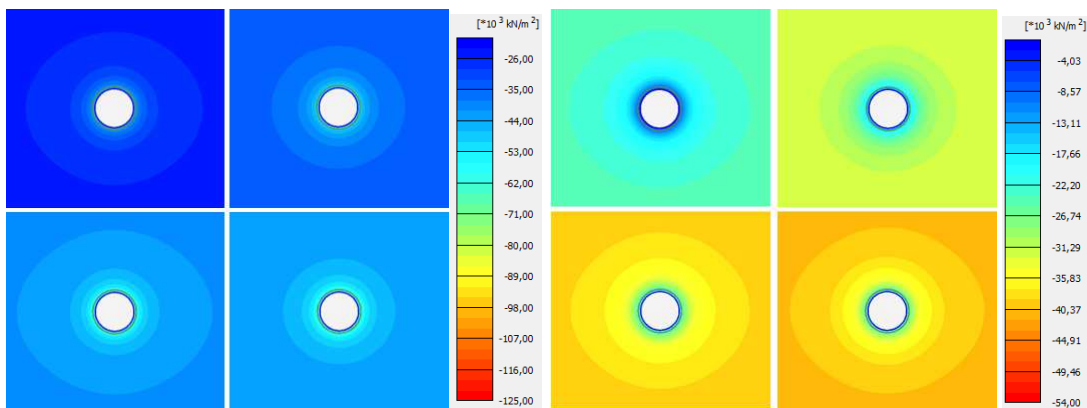


Figure 4 – Maximum (on the left) and minimum (on the right) principal effective stress around the wellbore in the case of hydrostatic stress regime as function of pore pressure reduction throughout the production time in the reservoir.

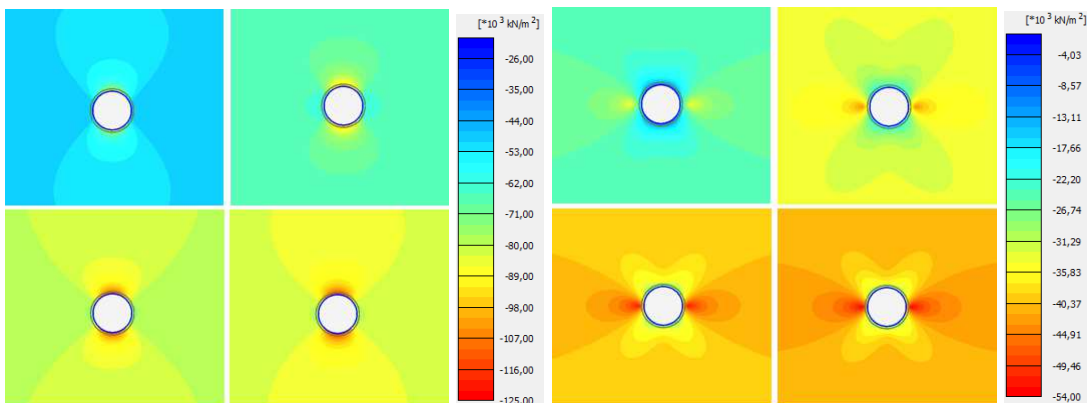


Figure 5 – Maximum (on the left) and minimum (on the right) principal effective stress around the wellbore in the case of the wellbore aligned with σ_h , as function of pore pressure reduction throughout the production time in the reservoir.

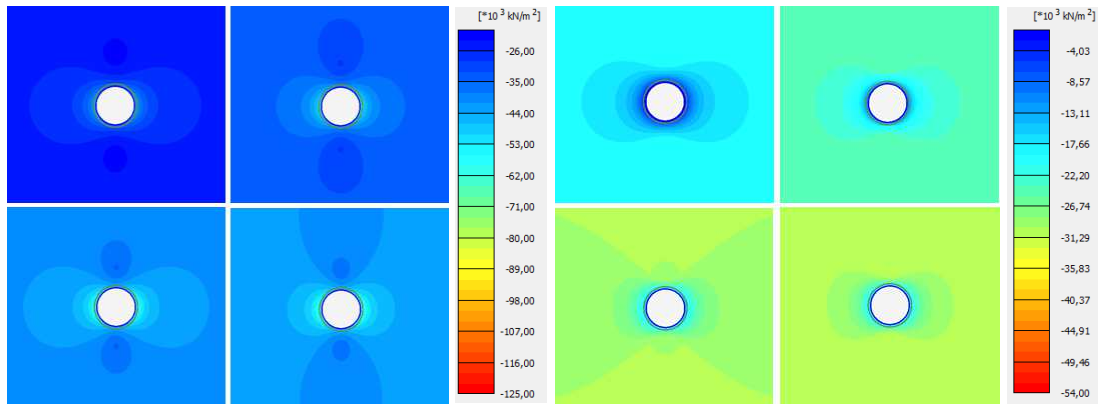


Figure 6 – Maximum (on the left) and minimum (on the right) principal effective stress around the wellbore in the case of the wellbore aligned with σ_H as function of pore pressure reduction throughout the production time in the reservoir.

As shown in figures 4, 5 and 6, there is an increment in the maximum and in the minimum principal effective stress with the pore pressure reduction during the productive period.

In the case of hydrostatic stress regime there is no expressive differences in distribution of stress around the wellbore. This is explained by the isotropy in terms of horizontal and vertical stresses.

When the wellbore is oriented in the direction of minimum horizontal stress (σ_h), the maximum principal effective stress (σ'_1) is greater in the direction of vertical stress, and the minimum principal effective stress (σ'_3) is greater in the direction of maximum horizontal stress, for all the production stages. This is due to the anisotropy between the pre-existing horizontal and vertical stresses, where the pre-existing stress (horizontal) is two times greater than vertical stress.

For the case of the wellbore aligned with the maximum horizontal stress (σ_H), where the pre-existing horizontal stress is $\frac{3}{4}$ of the vertical stress, σ'_1 is greater in the direction of minimum horizontal stress and σ'_3 is greater in the direction of vertical stress.

The maximum and minimum principal effective stresses are greater in the case of the wellbore be parallel to the minimum horizontal stress direction.

Figures 7, 8 and 9 show the results for relative shear stress and maximum shear stress. In each figure, $P_p=37.23$ MPa (top left), $P_p=28.96$ MPa (top right), $P_p=22.06$ MPa (bottom left) and 20.68 MPa (bottom right).

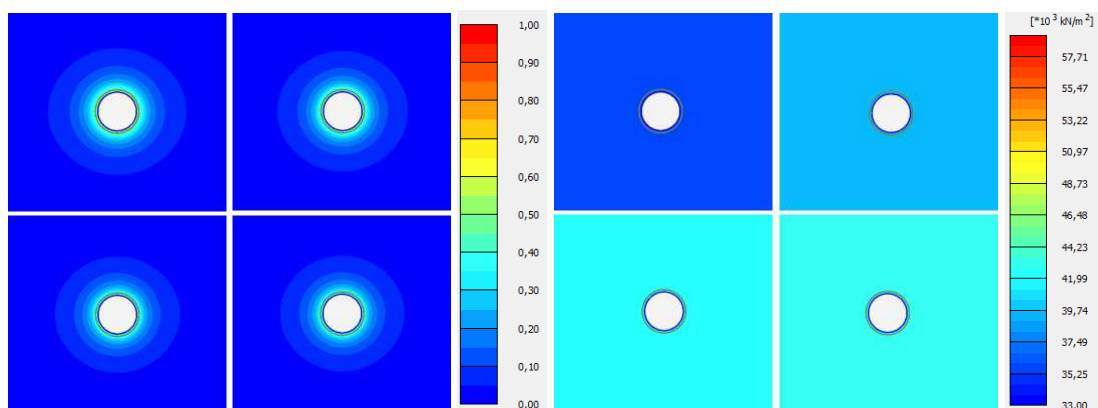


Figure 7 – Relative stress (on the left) and maximum shear stress (on the right) around the wellbore in the case of hydrostatic stress regime as function of pore pressure reduction throughout the production time in the reservoir.

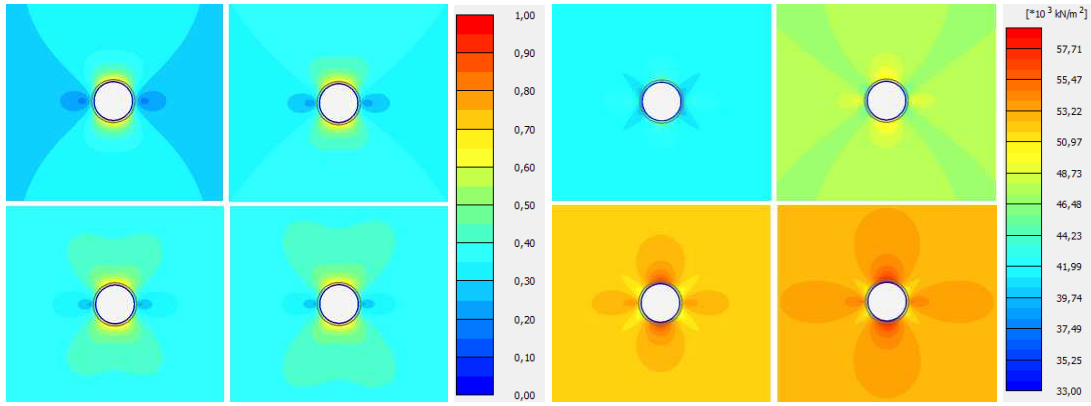


Figure 8 – Relative stress (on the left) and maximum shear stress (on the right) around the wellbore in the case of the wellbore aligned with σ_h as function of pore pressure reduction throughout the production time in the reservoir.

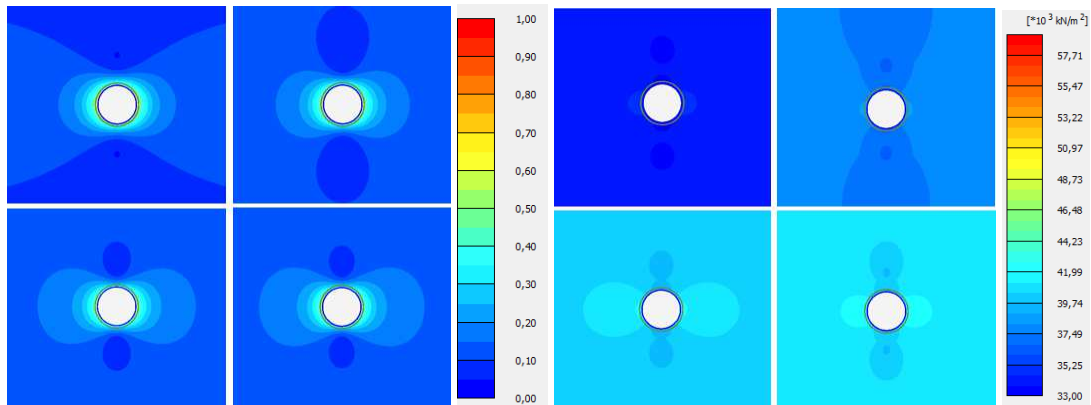


Figure 9 – Relative stress (on the left) and maximum shear stress (on the right) around the wellbore in the case of the wellbore aligned with σ_H as function of pore pressure reduction throughout the production time in the reservoir.

The relative shear stress (τ_{rel}) gives an indication of the relative proximity of the stress point to the failure envelope, and is defined as:

$$\tau_{rel} = \frac{\tau_{mob}}{\tau_{max}} \quad (2)$$

where (τ_{mob}) is the mobilized shear strength, that corresponds to the maximum value of shear stress (i.e. the radius of the Mohr stress circle), and (τ_{max}) is the maximum shear stress, which corresponds to the maximum value of shear stress for the case where Mohr's circle is expanded to touch the Coulomb failure envelope while keeping the centre of Mohr's circle constant.

From the τ_{rel} results we can conclude that, in all cases studied, there is no wellbore instability. The failure envelope is not touched, i.e., the τ_{rel} is always less than 1. Hydrostatic stress regime is the case where τ_{mob} is lower, with a value about 58% of τ_{max} . For the case of wellbore aligned with σ_H , τ_{mob} is 65% of τ_{max} . The maximum value of τ_{mob} , 82%, is observed in the case of the wellbore aligned with σ_h . These results are in accordance with the statements of Zeynali (2012), who says that in a strike-slip stress regime the higher the ratio of the horizontal principal stresses to the vertical stresses (σ_H/σ_v), the closer the drilling direction should be to the azimuth of σ_H for minimizing compressive shear failure (breakout).

From figures 7, 8 and 9, concerning the maximum shear stress, it can be observed the growing of the area subjected to greater stress, it is to say, the shear stress grows, spreading the influence radius of the wellbore.

The displacements in the monitoring points are compared in figures 10, 11 and 12. The maximum displacements occur at the wellbore wall, where there is a radial and tangential stress concentration. As the distance to the wellbore wall increases there is a reduction of displacement and a convergence in its magnitude.

In the case of hydrostatic stress regime, the displacements, in each point and for the same distance, are not altered with the pore pressure variation. The larger displacements occur in the up points aligned with the vertical stress (K, L, M and N). The shorter displacements occur in the down points (O, P, Q and R). The maximum displacement is 0.3633×10^{-3} m.

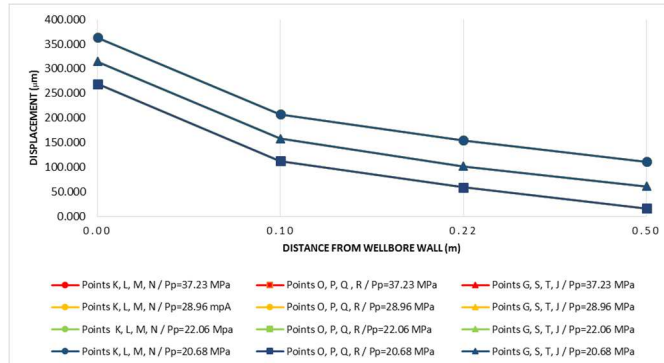


Figure 10 – Displacements in the monitoring points around the wellbore under a hydrostatic stress regime.

When the wellbore is oriented with the minimum horizontal stress direction, the displacements in the points aligned with the horizontal stress direction are greater than the displacements in the points aligned with the vertical direction. The shorter displacements occur in the down points (O, P, Q and R). The maximum displacement is 0.6645×10^{-3} m. The displacements in the direction of horizontal stress increase with a reduction of pore pressure in the reservoir. The opposite occurs in the direction of vertical stress.

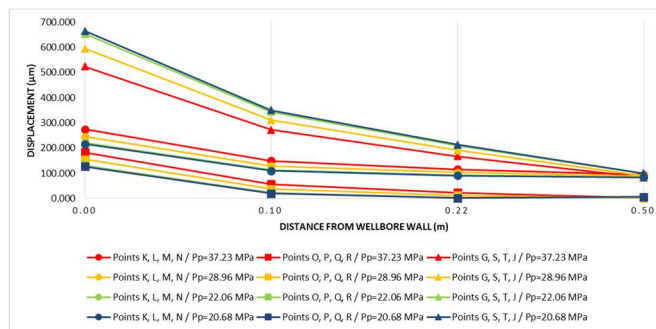


Figure 11 – Displacements in the monitoring points around the wellbore aligned with σ_h direction.

Considering the case of the wellbore parallel to the maximum horizontal stress direction, the displacements are greater in the vertical stress direction, in this case, in the up points (K, L, M and N). The maximum displacement is 0.4000×10^{-3} m. The displacements increase in the vertical stress direction and reduce in the horizontal stress direction, with the pore pressure reduction.

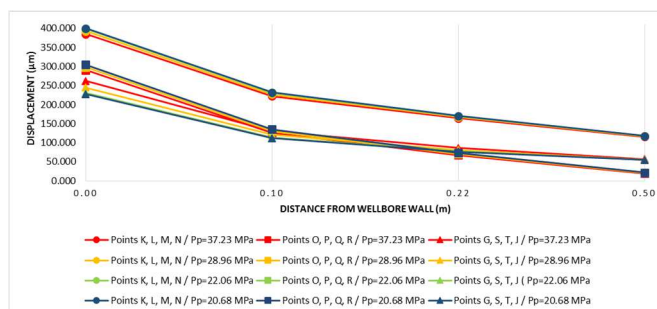


Figure 12 – Displacements in the monitoring points around the wellbore aligned with σ_H direction.

Comparing the displacement values and the maximum shear stress and the relative stress, we can conclude that strains do not exceed the plasticity limit of the rock, because, if that occurred, the Coulomb failure envelope, representative of the failure domain, would be touched. As observed, this situation does not happen.

5 Conclusions

In this work, by application of specific calculation tools and methods as the ones used – Plaxis code and Finite Element Method – it was possible, from static values of fluid pore pressure, representative of it in several specific periods throughout the production time in the reservoir, simulate a situation resulting from the dynamic of fluid flow, which allowed to study the stress/strain relationship around the wellbore during the production time in each stress regime considered, as well as the wellbore stability.

The following conclusions may be established from this work:

- The pore pressure reduction, in the reservoir, throughout the productive period leads to an increment in the effective stresses.
- The maximum and the minimum principal effective stresses and the displacements are greater in the case of the wellbore be parallel to the minimum horizontal stress direction.
- In all cases analysed, the wellbore is stable, since the Coulomb failure envelope is not touched.
- The mobilized stress is greater in the case of the wellbore aligned with the minimum horizontal stress direction.
- From all scenarios analysed, the case of the wellbore aligned with the minimum horizontal stress direction is the case that shows the worst situation in terms of geomechanical conditions.
- The greater the difference between *in situ* stresses the greater are the stresses and the displacements around the wellbore, which reveals the importance of stress field anisotropy on wellbore stability.

For future work, it is suggested a three-dimensional geomechanical analysis, using a 3D version Plaxis software, in order to take advantage of the model in its potential for a geomechanical analysis. It is also suggested an investigation about the influence of fractures in shale formation on wellbore stability, focusing the interaction of fractures occurrence with the wellbore orientation, *in situ* stresses and rock strength anisotropy. Finally, it would be profitable the availability of field data, in order to do a more realistic approach to the problem, comparing the results, obtained from simulations, with field data. Thus, it would be possible to test and refine the results and perform the model.

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