ORIGINAL ARTICLE

Wellbore stability analysis based on geomechanical modeling using finite element method

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Abstract

The analysis and prediction of the wellbore stability is considered as one of the sensitive and critical factors in oil wells' drilling operations. Parameters affecting well stability include region's in situ stresses, pores' water pressure, rock strength, drilling fluid pressure and drilling direction, respectively. In general, in situ stresses and rock resistance are some of the uncontrollable parameters affecting the wellbore and will become possible only by adjusting controllable parameters such as fluid pressure and drilling direction to avoid well instability problem occurrence. This paper has tried to investigate well instability problem in one of the Asmari Reservoir wells in one of the southwestern Iran fields in different ways and present the necessary approaches and suggestions for better promotion of drilling operations in the aforesaid field. To achieve induced stresses around the wellbore, numerical method and Phase 2 software have been used. Rock mechanical parameters including modulus of elasticity, Poisson's ratio, cohesive bond, friction angle, over-burden floor stress amount, minimum and maximum horizontal stresses along the well depth have been investigated and their variations have been shown and then, to simulate the wellbore stability, these data were entered at a cross-section (2380 m) into the Phase 2 software and the output of this software including stresses, displacements around the wellbore has been analyzed finally after solving with finite element method.

Keywords Wellbore stability · Fracture · Collapse · Drilling operation · Finite element method

Introduction

Geomechanics is a science which deals with identifying, modeling and controlling rock deformation. Understanding and managing these deformations risk results in reducing different practical subcategories' risk such as well stability, sand production and hydraulic fracturing (Kristiansen 2004). Geomechanics consists of a series rock mechanics, soil mechanics and fracture mechanics that are the root of many drilling, production, and development phases' problems of hydrocarbons fields and is generally a science that deals to study and analyze earth behavior against stresses (Zoback 2010). These stresses may be natural ones inside the ground or induced stresses by humans in different operations such as drilling. Therefore, as the name turns out, the key to the physical and mechanical problems with interaction of materials at different earth depths and existing stresses includes in the area of this science studies. In fact, the purpose of earth in geomechanics means all materials that are seen from the shallow depth with the highest operations that the mankind has ever achieved them in drilling. The mentioned materials at low depths are generally soils that usually include not-hardened masses and hard and dense rocks at high depths (Zoback 2003).

Among the widespread applications of petroleum geomechanics, analytical studies of well stresses have a special position and importance, because the wells have become more complex in terms of well stability affected parameters due to passing the time and increasing the need to exploit hydrocarbon reserves and drilling operations perform in environments with harder conditions (Fjar et al. 2008). In addition to the technical challenges of drilling these wells that require more time and expenses, occurrence of any instability in the wellbore can increase the well expenses a lot. According to the performed estimates based on data from drilling around the world, at least ten percent of the wells defined budget spends in the face of unforeseen

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operations which are associated with the wellbore instability (Liu et al. 2015).

Well stability means a state where the well diameter remains constant during the drilling interval and is equal to the drill diameter, whereas well instability refers to the conditions such as cracking with collapse of the well casing on the other hand, which generally achieves as the result of accurate recognition absence of the formation rock mechanics properties (Zoback et al. 2003).

Research background

Sufficient information on the amount and direction of in situ stresses should be available to analyzing stability and modeling of the wellbore which many studies have been conducted in this area. Bell calculated the amount and direction of stresses in 2003 using the average amount of group data (Bell 2003). In 2003, Zoback et al. examined a series of methods for quantifying and directing stresses in deep wells. These methods can be used in vertical and diversion wells. The results of these methods were associated with an error and are not so reliable (Zoback et al. 2003).

In 1998, Adenoy and Chenworth were among the first ones who used solids mechanics to analyze the stability of high slope wellbores. This study calculated stresses around the well based on linear elastic model and being isotropic. Consequences of these studies showed that when the well changes from vertical to horizontal mode, the probability of instability will increase (Adenoy and Chenevert 1998).

Bernt and Aadnoy applied the elastoplastic model to the wellbore analysis in 2004. Fracturing experiments on the core showed that the linear elastic model underestimate the fracture pressure. Therefore, they used the elastoplastic model that also described the fracture behavior (Bernt and Aadnoy 2004).

Elastic and elastoplastic models are usable for situations when a fluid does not penetrate the formation during drilling operation. Pro-elastic and pro-elastoplastic models take into consideration the changes in the rock cavity pressure too. These models provide a better prediction of the wellbore stability and also consider rock solidification by confined pressure.

In 2004, Tan also considered the effects of drilling fluid penetration in a study which done on the wellbore stability in the rift rock masses. In this study, common pair analysis was used to investigate the fractures and the effect of drilling fluid penetration into the fractures on the wellbore stability under isotropic and anisotropic stress conditions. The results showed that natural fractures and friction angle reduction due to drilling fluid penetration had a significant effect on wellbore stability (Tan 2004). This effect will be increased as the anisotropy increases. Therefore, it is necessary to consider the influence of drilling fluid penetration on the wellbore stability in such rocks.

Zhao et al. applied a double pro-elastic porosity model to compute the stresses of natural rift reservoirs in 2019 (Zhao et al. 2019). Because the elastic and pro-elastic models often uses for stability analysis in vertical wells and are not suitable for usage in porous formations with natural fractures. In these formations, most of the wells dig horizontally. The usage of pro-elastic models in porous reservoirs with natural rifts is also associated with errors.

The results of pro-elastic double porosity model usage showed that the wellbore stability strongly depends on the in situ stresses and well orientation. In strike-slip fault patterns, horizontal wells which are drilled along maximum stress have more stability during well drilling and completion. As well as, for normal stress patterns, wells that are drilled in the horizontal stress direction are more likely to be stable.

One of the most important parts of stability analysis is selecting the proper failure criterion. The most popular used failure criteria are the Mohr–Coulomb and Drucker–Prager criteria. Researchers have concluded that these two failure criteria predict different values for the minimum mud weight that keeps the wellbore stable. The Mohr–Coulomb criterion does not consider the intermediate principal stress influence, that is why it predicts the minimum mud weight highly, whereas the Drucker–Prager criterion considers the effect of intermediate principal stress and forecast this minimum mud weight low (Singh et al. 2019).

In 2006, al-Ajami and Zimmerman applied the Maggie–Coulomb failure criterion to the wellbore stability analysis and showed that this failure criterion is more accurate than Mohr–Coulomb and Drucker–Prager criteria in modeling. This failure criterion also takes into account the effect of the intermediate principal stress on the rock reinforcement (Al-Ajmi and Zimmerman 2006).

Yongfeng and Rangang used the Hook–Brown three-dimensional failure criterion in 2010 and the results they obtained for the minimum drilling mud weight were among the gained values from the Drucker–Prager and Mohr–Coulomb criteria (Yongfeng and Rangang, 2019).

Wellbore stability studies using geomechanical methods require knowledge of rock strength, pore pressure and principal stresses amount and direction. The methods designed to predict parameters such as mud weight and optimal drilling path are based on definitive analyses which is assumed that the parameters of the rock and the principal stresses are definitely specified, but in reality, the geomechanical parameters are not defined exactly. To quantitatively calculate the effects of these uncertainties, possible methods should be used.

Geological setting

Mansouri Oil Field is located in southwest of Iran, in Khuzestan plain, in the North Dezful Embayment area, about 60 km southwest of Ahvaz. The field is located to the north-west side of Ahwaz Field and from the west side, is in the Abteymour neighborhood and from north-east, in the vicinity of Azadegan Field (Fig. 1).

The Mansouri field had no exposure on the surface and was discovered by underground exploration by seismic operations in 1962. The presence of hydrocarbons in both the Asmari and Bangestan reservoirs was confirmed by digging the first exploration well in 1963. The length of this field at the water–oil contact surface is about 39 km and its width is about 3.5 km. Like many fields in this region, its structure follows the Zagros process (northwest–southeast).

Up to 60 wells have been dug in this field till now and Asmari Formation is vertically divided into 8 distinct sections consisting of limestone, sandstones and clay based on litology and porosity changes (Fig. 2), which sandstone layers hold major part of the available oil of the reservoir in themselves because of their high porosity and permeability and less water saturation. This classification is happened based on data from gamma, neutron, density and porosity diagrams of the well which obtained from petro-physical analysis to characterize the head of formations. Some of the important characteristics of the Asmari reservoir are as follows:

Sections one, six and eight are composed of carbonate rocks, while the sandstone facies are formed the major parts of sections two, three, four, five and seven.

Part I consists of dolomite rock with a significant amount of gypsum. Gypsum fills most of the paths between the pores, so oil could not replace the initial water during migration.

Sections two and three are the most important part of the Asmari reservoir, and much of the oil extracts from these sections. The porosity of these sections is 27 and 28.5%, respectively. In part two, the porosity percentage in the northern domain of the reservoir is better than in the southern one, as well as the ratio of oil shale to mud rock on both sides of the reservoir is better than the middle parts.

In part three, the amount of the shale on both sides of the reservoir is greater than the middle part. It is worth noting that most of the wells have been drilled and graphed to the end of section 14 (reservoir section) ultimately. The intended well is drilled up to a depth of 2686 meters and at the end of Zone 8.

Stresses around the well

Investigation of stresses around the well is strongly influenced by the direction of the well. Therefore, the stress scope is aligned to the well axis in the balanced wells and in the same direction. But in inclined and horizontal wells, surveying stresses around the well requires a series of coordinate transfers due to inconsistency of the stress scope with the main axis of the well.

Fig. 1 Geographical location of the studied area

Fig. 2 Longitudinal cross sections of the Asmari anticline
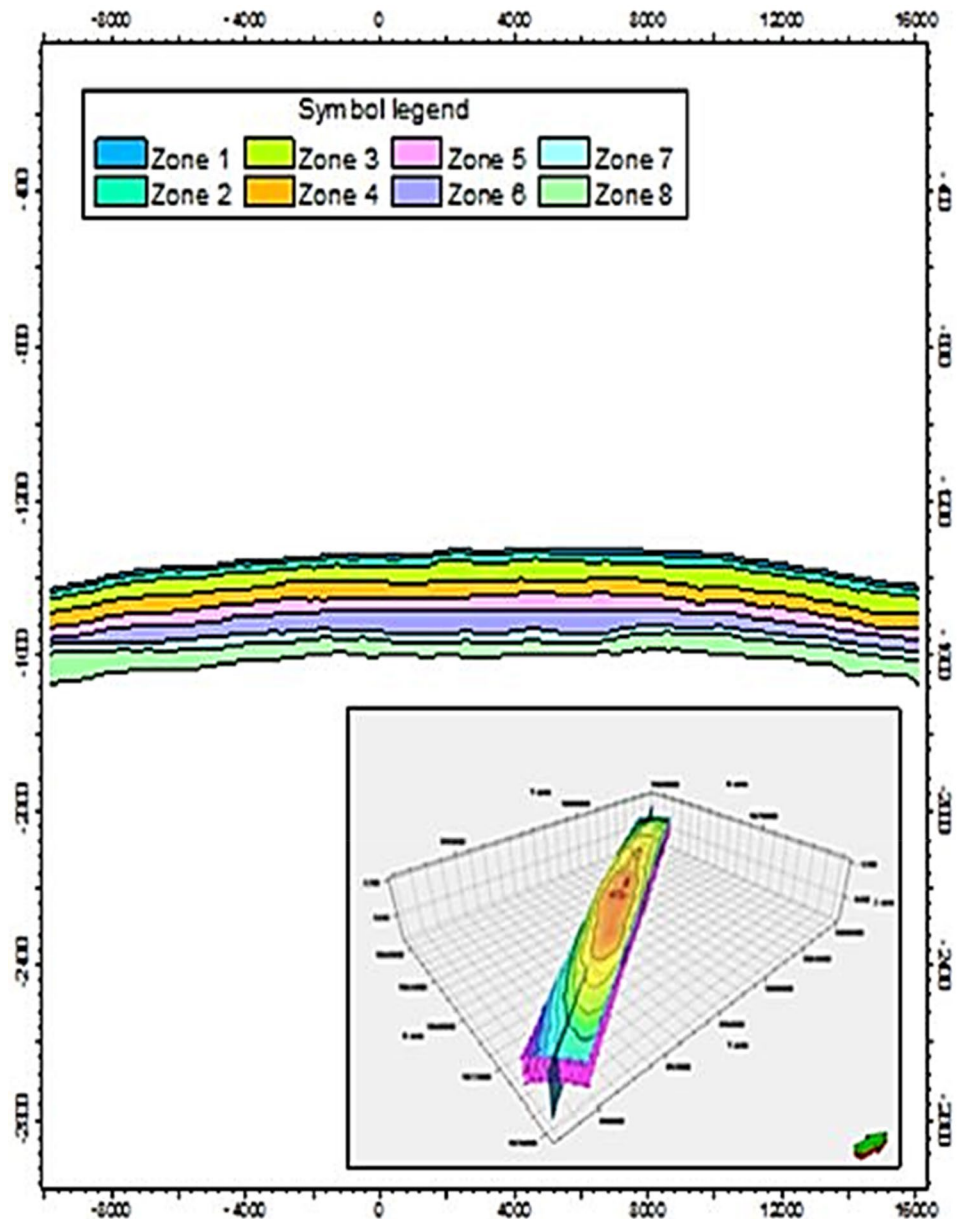
The concentration of the stress around a balanced drilled hole that is parallel to the main vertical stress Sv and in an elastic and isotropic environment is described by Crush relations. Similarly (Fig. 3), the stress status will change in the vertical and parallel directions to the wellbore with the creation of a cylindrical cavity in the ground, because the created empty space cannot tolerate the developed shear stress. As a result, there will be a stress concentration around the well that followed by a compressive stress extension (compression zone) along minimum horizontal in situ stress and will observe the compressive stress reduction along maximum horizontal in situ stress instead.

Since the fractures occur mostly around the wellbore ($a = r$); therefore, the stress distribution equations reduce to the effective stresses which include the pore pressure P_0 around the wellbore and are defined as follows:
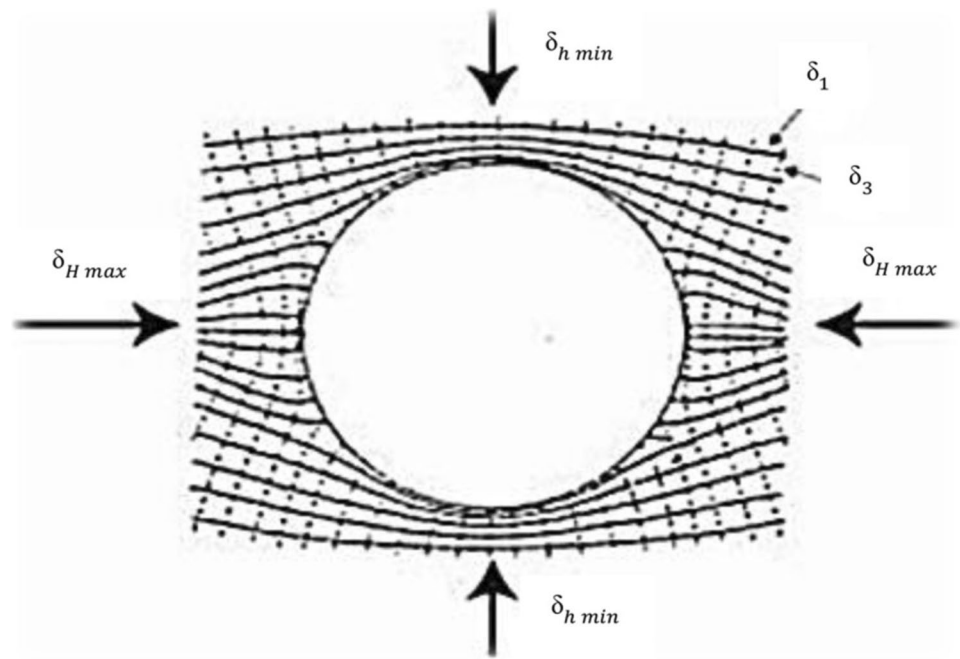
$$\sigma_{rr} = P_w - P_p \tag{1}$$

$$\sigma_{\theta\theta} = \sigma_X + \sigma_Y - 2(\sigma_X - \sigma_Y)\cos 2\theta - 4\sigma_{xy}\sin 2\theta - P_w - P_P \tag{2}$$

$$\sigma_{ZZ} = \sigma_Z - \vartheta\left[\left(2\left(\sigma_X + \sigma_y\right)\cos(2\theta)\right) + 4\sigma_{xy}\sin(2\theta)\right] - P_P \tag{3}$$

$$\sigma_{r\theta} = 2(-\sigma_{xz}\sin\theta + \sigma_{yz}\cos\theta) \tag{4}$$

$$\sigma_{r\theta} = \sigma_{rz} = 0 \tag{5}$$

Fig. 3 Stresses applied to an oil well

That $\sigma_{rr}, \sigma_{\theta\theta}, \sigma_{zz}$ refer to the radial, tangential and axial stresses, respectively, r is the distance from the well, P_w as the well internal pressure and ν refers to the Poisson's ratio and the θ angle relative to the axis around the well hole.

The presence of drilling fluid inside wellbore develops some balance inside the borehole. This refers to a balance in interactions between drilling mud and in situ stress field, where the drilling mud tries to keep the wellbore supported, while the in situ stresses attempts to make it unstable. On this basis, a secondary stress field is developed which is known as induced stress field or post-drilling stress field and includes three stresses:

Hoop stress, $\sigma_{\theta\theta}$

Radial stress, σ_{rr}

Axial stress, σ_{zz}

Induced stress field, which controls major issues in engineering operation, can be calculated depending on the well geometry and its orientation with respect to $S_{H\,max}$ and $S_{h\,min}$, using the following relationships:

In homogeneous, isotropic and elastic rocks where the vertical stresses are parallel to the well axis and also $i = a = 0$; the effective stresses around the vertical well are defined as follows:

$$\sigma_{rr} = P_W - P_P \qquad (6)$$

$$\sigma_{\theta\theta} = S_{H\,max} + S_{h\,min} - 2\left(S_{H\,max} - S_{h\,min}\right)\cos 2\theta - P_w - P_p \qquad (7)$$

$$\sigma_{zz} = S_v - 2\nu\left(S_{H\,max} - S_{h\,min}\right)\cos 2\theta - P_P \qquad (8)$$

$$\sigma_{\theta\theta} = \sigma_{rz} = \sigma_{r\theta} = 0 \qquad (9)$$

In the above relationship, the radial and tangential stresses are the function of mud pressure P_w, so any changes in drilling mud pressure cause these two stresses to change. When the mud pressure decreases, the tangential stress is increased and stands in compressive state and the radial stress becomes less than or equal to the mud pressure, which this phenomenon makes sense in equilibrium drilling operations with respect to the well designing. Therefore, the lower extent of mud pressure will cause the well falling in. Consideration to tangential stress will be a useful and effective method as it plays an important role in the instability of the well and depends on the size and direction of the stresses around; so if combined with the mechanical, thermal and rheological properties, extensive processes can be investigated.

Determination the geomechanical parameters needed for analysis

The resulted reservoir geomechanical parameters from dynamical investigations are obtained using acoustic logs (including shear compressive wave transient time) and density logs. By measuring those mentioned properties, the geomechanical parameters of the formation are calculated as follows:

$$E_d = \frac{9K\rho V_p^2}{3K + \rho V_p^2} = \left[\frac{\rho}{\Delta t_p^2 - \Delta t_s^2}\right] \times 1.34 \times 10^{10} \qquad (10)$$

$$K_d = \rho\left[V_P^2 - \frac{4}{3}V_s^2\right] = \rho\left[\frac{3\Delta t_p^2 - 4\Delta t_s^2}{3\Delta t_p^2 - 4\Delta t_s^2}\right] \times 1.34 \times 10^{10} \tag{11}$$

$$G_d = \rho V_P^2 = \left[\frac{\rho}{\Delta t_p^2}\right] \times 1.34 \times 10^{10} \tag{12}$$

$$V_d = \frac{1}{2}\frac{\left[\frac{V_s^2}{V_p^2}\right] - 2}{\left[\frac{V_s^2}{V_p^2}\right] - 1} = \frac{1}{2}\left[\frac{V_p^2 - 2V_s^2}{V_p^2 - V_s^2}\right] \tag{13}$$

$$\sigma_v = \int_0^Z \rho(Z)gdz = \rho gz \tag{14}$$

In situ horizontal stress estimates from the following equation:

$$\sigma_h = (v)/(1-v)\sigma_v - v/(1-v)\alpha P_p + P_p + \frac{E}{1-v^2}\varepsilon x + \frac{Ev}{1-v^2}\varepsilon y \tag{15}$$

As ρ_i refers to density, h_i for i layer thickness and a is the Biot's Coefficient in the above equations.

In δ_h, v is Poisson's ratio, α is Biot factor, P_p is pore pressure, E is the modulus of elasticity (static), ε_y is strain along the y-axis, and ε_x is the strain along the x-axis. Biot factor represents transmissibility of the rock and its value ranges between zero and one. For a porous and permeable reservoir rock, the value of biot factor is 1, while that of a non-porous rock is zero.

Experimental equations can be used to transform dynamic equations to static ones. For example, the following equation is used for the Young's modulus:

$$E_{static} = 0.414E_{dynamic} - 1.0593 \tag{16}$$

Once finished with calculating the moduli of elasticity in dynamic mode, the moduli should be converted into their corresponding static values. Because geomechanical and geological processes are so slow, i.e. static. To convert the dynamic moduli to static ones, the best approach is to use experimental data. However, due to lack of such data, a series of empirical relationships for the oil fields of study are used.

This relationship is based on the experimental data on the core sample in the study area.

The input data for geomechanical construction are obtained from the well logging operation. These data are shown in Table 1.

BS & CALIPER: The BS log shows the drill bit size that drilled the wells, which is usually a constant number and the CALIPER chart shows the diameter of the well, which shows the erosion and narrowing distances along the wells relative to the size of the drill bit.

GR: This log measures the radioactivity in the formation. This log measures the total amount of radioactivity, i.e. the reading of three levels of thorium, potassium and uranium. Most are used to detect shale beds, since they have the highest levels of radioactivity in shale (clay minerals).

DT: DT logs measure the sonic speed in the formation. This log is introduced as an audio log, and is one of the logs for measuring porosity in the well. The unit is based on microseconds per feet (us/f).

RHOB: This log measures the density of rock formations and is part of the porosity measurement logs. The unit of this log is g/cm^3.

PEF: The photoelectric log that performs its own depiction along with the chart or density tool (RHOB) and can better detect lithology.

NPHI: The neutron log performs its measurements based on the amount of hydrogen in the formation. This log is among porosity log and is usually calibrated based on the lithology of lime.

RT & RXO: These logs are part of the logs for measuring the resistance of the formation. Resistance logs have various types that are divided according to the type of measurement, the drilling fluid in the well and the depth of the search. The unit of all resistance logs is ohm-m.

Results and discussion

The sonic logs (which only provide us the interval passage time of compressive waves), the neutron porosity log and the total density log are driven in the studied well. These logs' data graphs are available from depths of 2380 to 2837 meters. In this paper, some modeling is also performed using Phase 2 software and finite element method and thereby the behavioral status of the rock around the wellbore will be examined in two-dimensional cross-section. The results obtained from software modeling predicted perfectly elastic steady conditions for the current well conditions at the studied sections another time. Thus, by comparing the results of the Phase 2 software modeling with the results of the analytical studies, it can be stated that analytical method can be used in addition

Table 1 Logging input data

Well name	Wire-line logs									
Well-A	RXO	RT	DRHO	PEF	RHOB	NPHI	DT	GR	CALI	BS

to numerical methods referring to the Mohr–Coulomb criterion of conservative due to the neglect of the effect of the average principal stress on the rock resistance. It should be noted that the Mohr–Coulomb criterion can be suggested as a suitable criterion for providing an almost accurate analysis and of course compatible with oil geomechanical studies in numerical method.

The analysis of horizontal and vertical stresses is illustrated in section 2380 (Figs. 4, 5, 6, 7, 8, 9).

In order not to affect the boundaries on the results, the external dimensions are considered sufficiently large in designing the model. For investigating in situ stresses in the region, the obtained stress condition number 1 from the stress polygon has been considered, whereas two horizontal stresses are assumed equal and the vertical stress equals to the overburden weight.

Two stages of calculation are considered in the analysis which is done by the software. The first stage applies to the model before in situ stresses of drilling the well. Of the three existing in situ stresses, both minimum and maximum horizontal stresses affect the lateral model boundaries.

In the second step of the calculations, it is assumed that the well is drilled. The conditions of minimum and maximum stresses and the amount of displacements around the
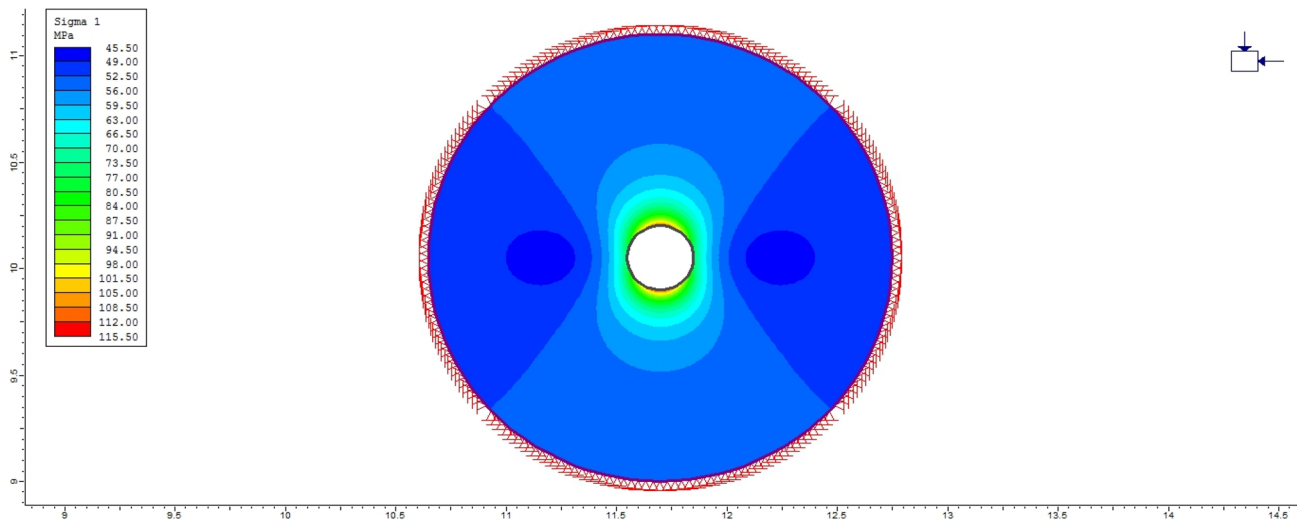

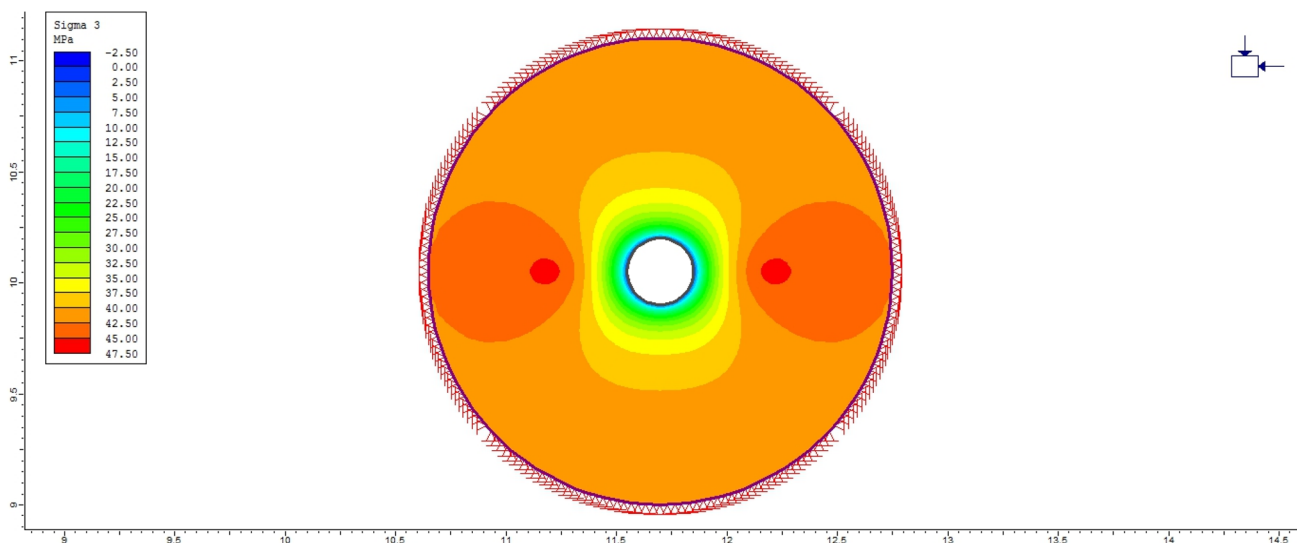**Fig. 4** Maximum principal stress distribution of the wellbore with depth section of 2380

Fig. 5 Minimum principal stress distribution of the wellbore with depth section of 2380. The minimum principal stress distribution on the wellbore is shown
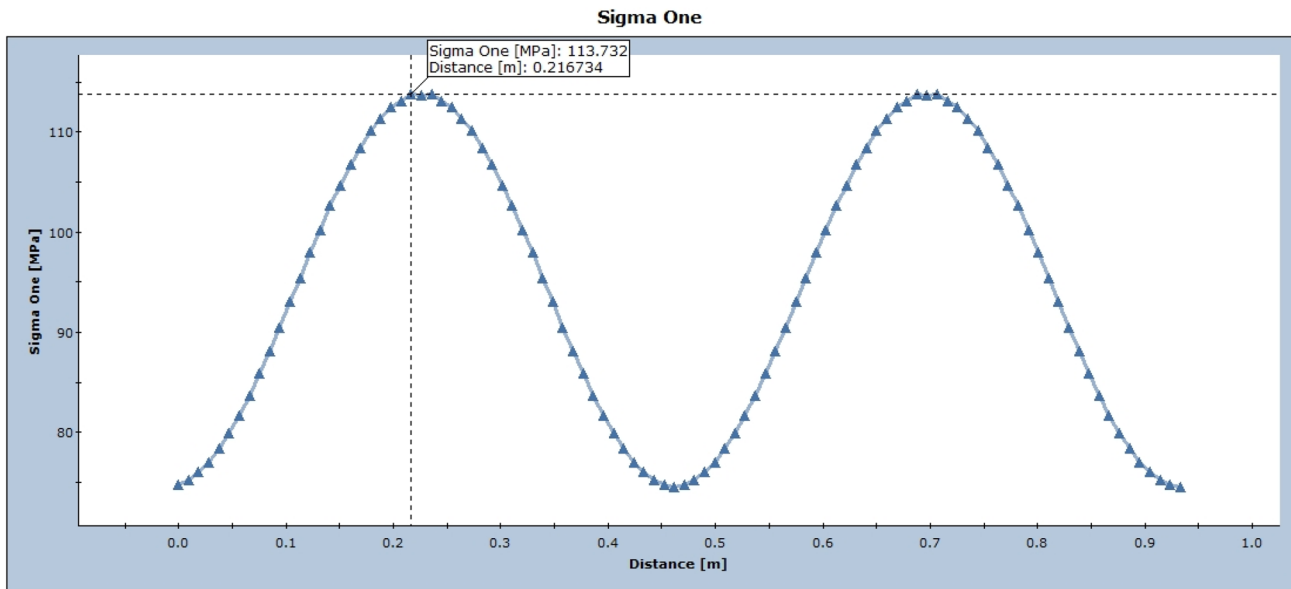
Fig. 6 Maximum principal stress variations around the wellbore toward the distance from the depth 2380 wall
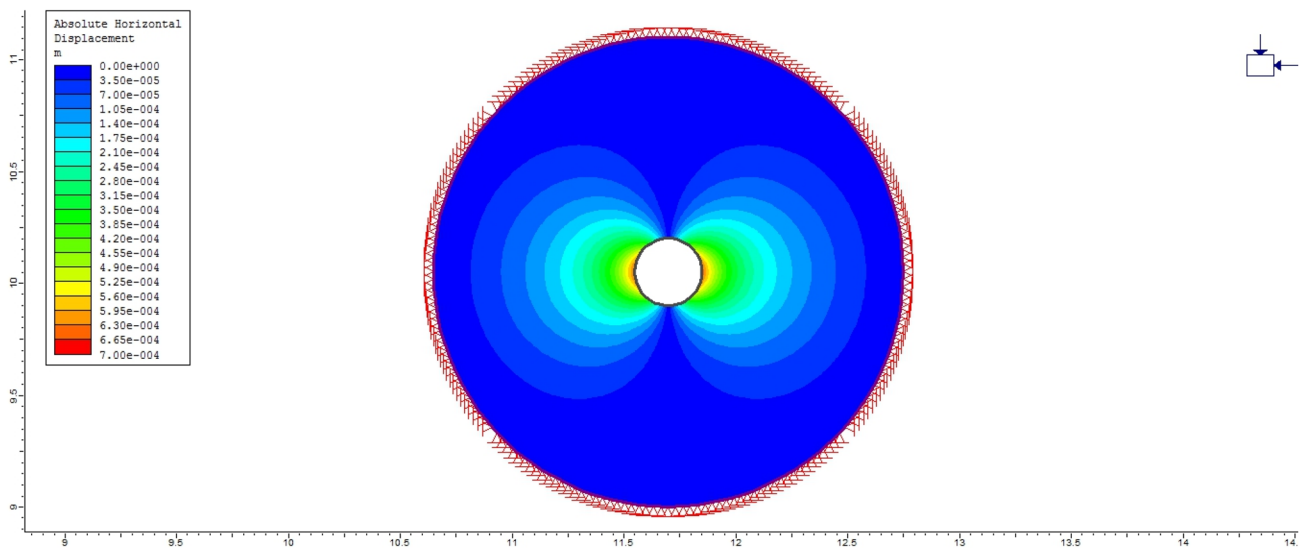

Fig. 7 Horizontal displacements distribution around the wellbore of the 2380 depth section

well are calculated by running a program special to the designed computational sections (Fig. 4).

The results of the analysis showed some negligible displacement values around the wall that can be neglected. According to the existing tectonic maps of the region, the mentioned well is located at a point where its stratification is horizontal (Fig. 6).

The section cross at which the well stability analysis is performed is at a high depth which has not any effect on the calculations due to the high anisotropic confinement pressure. Therefore, awareness of the stratification plates

position state and shale anisotropy direction can affect on the analysis of well stability stresses (Fig. 7).

The results of the analysis showed some insignificant displacement values around the wall that can be ignored. According to the available tectonic maps in the area, the well is located at a spot that has a horizontal stratification. The section at which the stability analysis of the well is performed is at a high depth that does not affect the calculations due to the high anisotropic confinement pressure. Thus, knowledge of the positioning status of the stratification
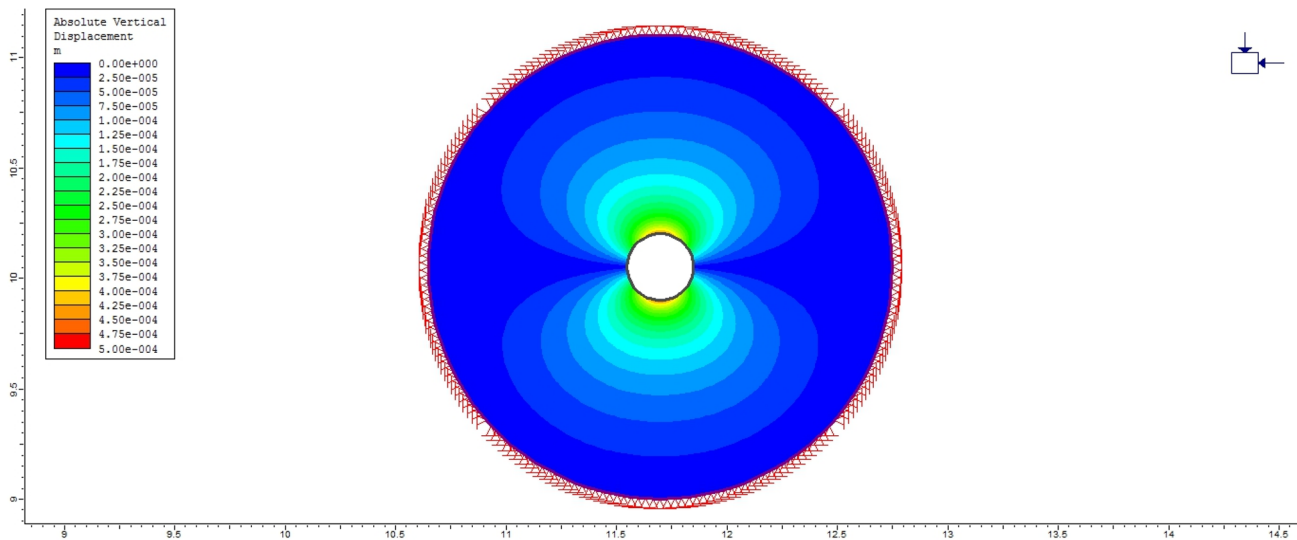
Fig. 8 Vertical displacements distribution around the Wellbore of 2380 depth section
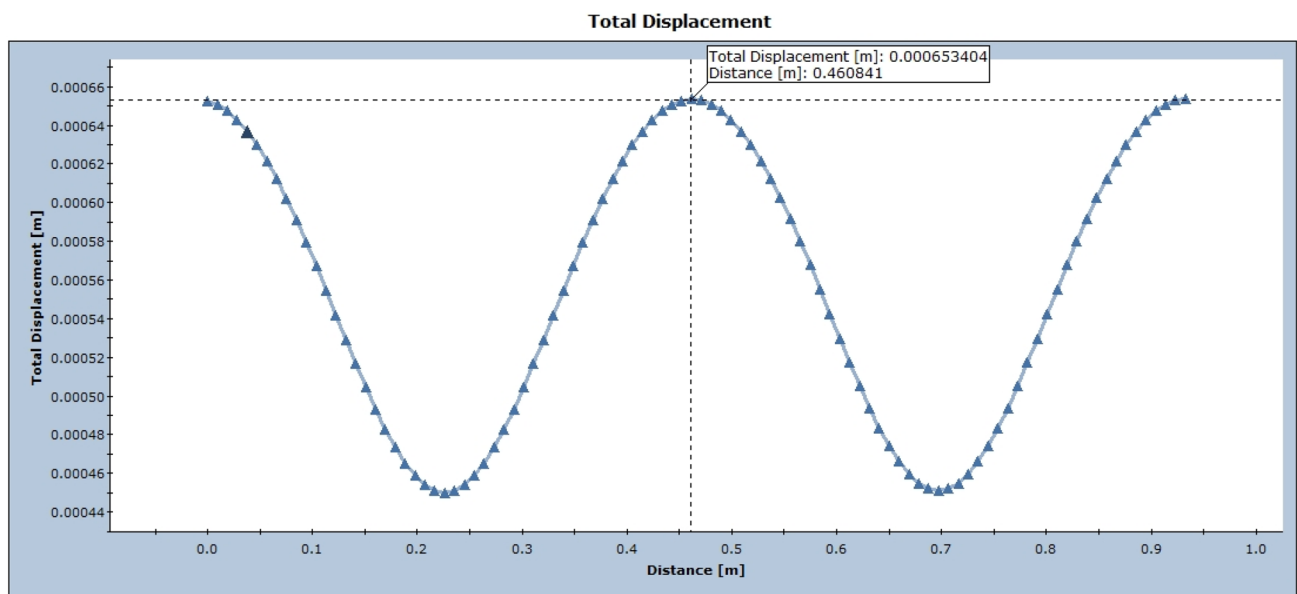

Fig. 9 Induced displacements to the wellbore

plates and the anisotropy direction of the shale can influence the well stability stresses analysis (Fig. 8).

As shown, the highest principal stress value is 113 MPa and the lowest induced stress value is 74.59 MPa and the maximum wellbore displacement is 0.65 mm.

According to Fig. 9, the greatest induced displacement to the well is at a distance of 46 cm from the wellbore.

Conclusion

Performing all studies of petroleum geomechanical basin including well stability studies, etc. requires construction of a precise geomechanical model so that can get through it to a complete understanding of rock mechanics

properties, stress conditions, pore reservoir pressure and well pressure and can provide desired results accordingly. In this paper, the modeling was done using Phase 2 software, whereby the behavioral status of rocks around the wellbore at a depth section of 2380 meters examined. The results obtained from the software modeling predicted the fully elastic stable state again for the current well conditions at the studied sections cross. Therefore, by comparing the results of the Phase 2 software modeling with the gained outcomes of the analytical surveys, can be commented that according to the Mohr–Coulomb criterion conservativeness due to disregarding the average principal stress effect on the rock resistance; analytical methods can be also used in addition to the numerical method. It should be noted that the Mohr–Coulomb criterion can be proposed as an appropriate criterion for presenting an approximately accurate and albeit consistent analysis to the petroleum geomechanical studies. Due to the analysis performed by Phase 2 software and using finite element method in the mentioned well, the maximum horizontal stress was applied at a depth of 2590 meters and the Young's modulus that defines the deformation was reached the maximum value at a depth of 2440 meters. Likewise, the results of finite element analysis indicate that the highest principal stress was 113 MPa at 2380 m depth and the lowest induced stress value was 74.59 MPa and also the maximum wellbore displacement was 0.65 mm.

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