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CASE REPORT

Evaluation of Wellbore Stability by Analytical and Numerical Methods: A Case Study in a Carbonate Oil Field

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ABSTRACT

The instability of the wellbore has significant effects on drilling, causing delays in operations, increasing costs, and ultimately may result in the abandonment of wells. Nowadays, it is possible to stabilize a wellbore by changing the drilling mud composition. With the help of rock mechanics and knowledge of the mechanical properties of the formation, the optimal path for the drilling of the well and the window of the mud is determined. Several features of the formation are influential in wellbore design; knowing these features is necessary for designing optimal mud weight to ensure wellbore stability. In practice, analytical methods for the calculation of the optimal mud weight are more convenient than numerical ones because the latter needs information on many samples that are usually unknown at the commencement of the project. This research investigates the wellbore stability in the Kupal carbonate oil field using an analytical method with three rock strength criteria of Mogi-Coulomb, Mohr-Coulomb, and Hoek-Brown failure. The authors conclude that the Mogi-Coulomb criterion predicts a minimum drilling mud pressure and is more conservative. This is due to the use of its intermediate stress.

1. Introduction

Underground formations always suffer from vertical compression stresses (upper layer weights) and horizontal stresses (lateral strain range) loads. The drilling operation perturbs the natural stress balance in the rocks and generates a high risk in terms of pollution, fueling climate change, disrupting wildlife, and damaging public lands [1]. When a well is drilled, the equilibrium of the area in which it is drilled is disturbed. The wellbore around it tries to restore the balance of the stress field. As a result, stress concentrations are created around the wellbore and penetrated the formation. In the absence of stability, there will be a failure in the wellbore and formation [2]. We need a deterrent as a pressure compensator to prevent the breakdowns, which is mainly the fluid (drilling mud) hydrostatic pressure. Zhang et al., (2009) [3] examined five failure criteria on various rock specimens to determine the best

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criterion for the wellbore stability analysis. Accordingly, they concluded that the 3D Hoek-Brown and the Mogi-Coulomb criteria are appropriate for wellbore stability analysis [3-5]. Al-Ajmi and Zimmerman (2006) [4] proposed using the Mogi-Coulomb criterion to predict the brittle shear failure of rocks. This criterion was shown to accurately model laboratory failure data on a range of different rock types McLean and Addis (1990) [6]. Using this Mogi-Coulomb criterion, they developed improved stability models for vertical, horizontal, and deviated boreholes [7]. Chatterjee and Mukhopadhyay (2003) [8] used ANSYS finite element software and investigated stress around a wellbore to study the effects of fluid pressure during drilling. Hoang et al. (2004) [9] investigated wellbore stability in multilateral junctions using the finite element method. They showed that the orientation of junction and in situ stresses both have a significant impact on well completion and stability. Salehi and Hareland (2010) [10] investigate wellbore stability in underbalanced drilling concerning equivalent circulating density with both Finite Explicit and finite-Element codes to cross-check the results [11,12].

In this paper, we have first used the Hoek-Brown, Mohr-Coulomb, Mogi-Coulomb, criteria to determine the optimum drilling direction and mud pressure for a wellbore located in the Kupal carbonate oil field. Then the finite difference method was used to show the validation and accuracy of predicted mud pressure and investigate the wellbore stability in different vertical, horizontal, and deviated states. The Kupal oil anticline is one of the most important structures in the Dezful embayment that is located northeast of the Ahvaz city and north of the Marun oil field. Recent deposits and Lahbari members of the Aghajari formation have formed the surface outcrops, and the Asmari formation with seven reservoir layers is the main reservoir rock in this oil field.

2. General and Geomechanical Information on the Kupal Carbonate Oil Field

The Kupal field is one of the Iranian oil fields. which is located in Khuzestan province and Haftkel city capital of Haftgel County. The length of this square is 39 km and its width is 4 km. The average crude oil production capacity of the Kupal field is equal to 91,000 BPD of crude oil, which is made through thirty-two active wells in the Asmari and Bangestan reservoirs of this field. The Kupal oil anticline is a fault-related (detachment fold) and asymmetric fold, in which the middle parts have been distinguished as potential zones of dense fracture development due to longitudinal curvature. The southwest limb in many parts and the northeast limb in the middle parts indicate zones with high fracture density, and the axial bending of the Kupal anticline is a result of the movement of deep faults. In situ stresses, geomechanical, and fluid flow information related to the Kupal carbonate reservoir in the wellbore at the depth of 3791 m are listed in Tables 1 and 2 [12].

Table 1. In situ stress and geotechnical parameters for wellbore stability analysis in the Kupal oil field [12].

Wellbore parameters	**Value**
Overburden Stress (MPa)	96.7
Maximum Horizontal Stress (MPa)	59.4
Minimum Horizontal Stress (MPa)	44.5
Cohesion (MPa)	27
Friction Angle (deg.)	40
Poisson's ratio	0.3
Density (gr/cm^3)	2.7
Young's modulus (GPa)	44
m_i	31
mb	11
S	0.036
D	0
GSI	70

Table 2. Parameters of formation fluid flow [12].

Pore pressure (MPa)	31.1
Permeability (md)	3
Porosity (%)	8
Oil density (gr/cm^3)	0.692
Fluid modulus (GPa)	0.63

3. Rock Strength Criteria

Mogi-Coulomb criterion

The Mogi-Coulomb model is an extension of the Mohr-coulomb criterion for predicting a failure condition in a 3D stress plane in the true triaxial test space. Mogi in 1971 carried out a polyaxial experiment and deduced that for several rock types the intermediate principal stress influences the rock strength. Therefore, while a fracture is generated, it will be in the direction of intermediate principal stress along a plane [4].

Mohr-Coulomb criterion

Mohr-Coulomb criterion model is based on the 2D Mohr's stress circle, which has been in for analyzing rock failure. Coulomb concluded that failure will occur along a plane due to shear stress acting on the plane. According to Coulomb's failure theory, the required compressive stress for failure will be increased linearly by increasing the confining stress [13,14].

Hoek-Brown failure criterion

The Hoek-Brown Failure criterion was developed to predict the ultimate strength of intact rocks and rock masses. Over the years, it has been adapted to specific rock masses and modified to fit non-linear models. It gives a more practical estimation of rock strength compared to the Mohr-Coulomb criterion. It can be used to calculate the mud pressures corresponding to the lower and upper stable mud weight windows [15,5].

4. Wellbore Stability Analysis by Analytical Method

For this analysis, parameters such as Young's modulus, Poisson's coefficient, pore pressure, main stresses, constant coefficients of rock material, etc. Are obtained from well charts and analysis of laboratory cores that are used to calculate the pressure and weight of the well Drilling is required. Rock failure is a very complicated process that is still not fully understood. To further simplify the analysis, it is assumed that the homogeneous and isotropic rocks and the pressure profile of the well are assumed to be the same.

To calculate the main stresses, these steps are done using coding in MATLAB software and predict the pressure, and weight of drilling mud in different directions of the well to prevent the instability of the wellbore, the results are presented in the of form three-dimensional and two-dimensional shapes and tables.

A field study was conducted on a carbonate formation in the Kupal carbonate oil reservoirs, in which a well with a pressure of 40 MPa and a weight of 42.29 (PCF) was drilled successfully and no reports of instability were provided.

Figure 1 shows the minimum required pressure and weight of mud for different wells for the Hoek-Brown, Mohr-Coulomb, and Mogi-Coulomb criteria. The results are about 3791 (m) deep. In the Hoek-Brown and Mogi-Coulomb criteria, the minimum drilling mud pressure increases with increasing azimuth and well deviation, because if we continue with drilling operations with the same pressure in the vertical section of the well, because the vertical stress is more than two horizontal stresses may cause the failure to a wellbore. But in the Mohr-Coulomb test, this pressure is reduced from a deviation angle of 20 degrees, which may be due to the tensile strength considered by this criterion. The Hoek-Brown criterion predicts that the single axial compressive strength of the rock, the minimum pressure, and the weight of the mud for drilling are more than Mohr-Coulomb, with an increase in the angle of deviation close to the Mogi-Coulomb criterion. The Mogi-Coulomb criterion estimates the minimum pressure fluctuation of more than two other criteria, which indicates that the intermediate stress affects the estimation of the minimum pressure and provides a better prediction of the pressure of the mud as a result, the minimum pressure and mud weight required is affected by the wellbore.

Figure 2 shows the maximum pressure and mud weight required for different aspects of the well based on Hoek-Brown, Mohr-Coulomb, and Mogi-Coulomb criteria. The results are about 3791 (m) deep. In all three criteria, the maximum pressure and the weight of the drilling mud decrease with increasing azimuth and the deviation angle of the wellbore, because if the pressure and the weight of the mud that is drilled in the vertical part of the wellbore, the deviated part of the wellbore are drilled with the same amount of pressure and weight mud. Due to the difference in the values of minimum and maximum horizontal stresses is that the wellbore suffers from tensile failure in the direction of the minimum horizontal stress, which causes the mud loss and blow out of the well.

In Figure 3, the minimum drilling mud pressure and the angle deviation of wells in the azimuths of 0° and 90° for the three criteria of the Mogi-Columbus Mohr-Columbus, and Hoek-Brown defects, are shown. The Mogi-Coulomb failure criterion predicts the maximum, minimum pressure, while the Mohr-Coulomb criterion advances the minimum, minimum pressure and decreases from a further 20 degrees to a further angle, which can be due to the tensile strength this is a failure criterion. Because the value of the lower limit of drilling mud pressure is close to and even less than the pore pressure, the closeness of the horizontal stress to the minimum horizontal stress is minimal. Therefore, in this condition, horizontal drilling (sub-equilibrium) is difficult and not recommended. In general, if the horizontal tension is at a maximum near vertical stress, the drilling mud safety window margin is wider and horizontal drilling is better and easier and recommended. Conversely, if the horizontal stress is at a maximum from the vertical stress and in other words near the horizontal stress is minimal, the drilling mud safety window margin is smaller and narrower, and the amount of the bottom of the drilling mud pressure is close to and even lower than the pressure. Drilling is difficult and not recommended.

In Figure 4, the maximum drilling mud pressure is shown in the wells in the azimuths of 0° and 90° for the three criteria of the Mogi-Coulomb, Mohr-Coulomb, and Hoek-Brown defects. The Hoek-Brown failure criterion predicts the highest maximum pressure in azimuth at 90°, and the Mogi-Coulomb criterion predicts the maximum peak pressure. The Mohr-Coulomb and Hoek-Brown benchmarks are close at 90° azimuth. The Mogi-Coulomb

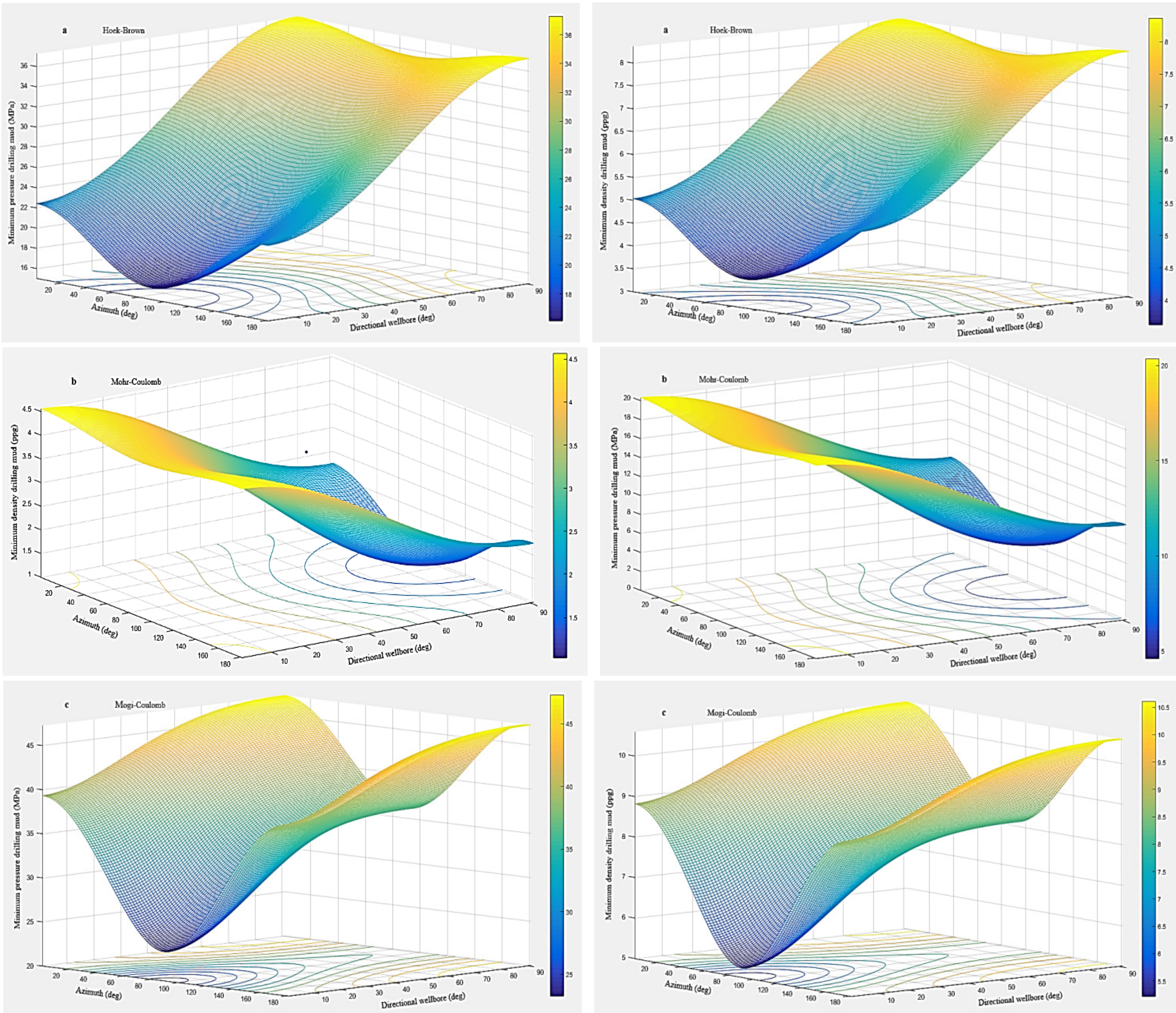

Figure 1. Minimum pressure and weight mud requirements based on azimuth and wellbore angle deviation using a) Hoek-Brown, b) Mohr-Coulomb and c) Mogi-Coulomb.

criterion in the azimuth 0° to the deviation angle of 30° is the maximum, maximum pressure of the mud and from this angle, then, predicts the minimum, maximum pressure of the mud. From a deviation angle of 30 degrees, the Hoek-Brown criterion predicts the maximum peak pressure. Therefore, the Mogi-Coulomb criterion is better than the other two criteria, because, in terms of tensile failure, the wellbore is safer.

Figure 5 shows drilling mud safety window the Hoek-Brown (a), Mohr-Coulomb (b), and Mogi-Coulomb (c and d) criteria are based on the angle of deviation and azimuths of 0, 30, 45, 60, and 90 degrees than for the Mogi-coulomb criterion separate shows the minimum and maximum differential pressure graphs. Based on this form, at zero angle of deviation, the pressure range of drilling mud is high due to the overcoming of shear failure due to the vertical deformation and with the deviation of the well from the vertical position, this area becomes smaller so that the well is deviated from the vertical state, the horizontal stresses of the vertical stress and therefore, if the minimum pressure is not increased, by increasing the angle of the deviation of the well, causing the wellbore shear failure, and if the maximum pressure of the mud does not decrease, by increasing the angle of the deviation of the well, the tensile deflection of the wellbore is in line with the minimum horizontal tension, and the loss of mud and eventually blow out in the wellbore.

To validate these models, the criteria are evaluated on a wellbore that has been successfully excavated.

Figure 5, as mentioned above, shows the minimum pressure and mud weight in terms of the deviation angle and azimuth at a depth of 3791 (m). The Mogi-Coulomb criterion predicts the highest minimum pressure and drilling mud weight, while the Mohr-Coulomb predicts the

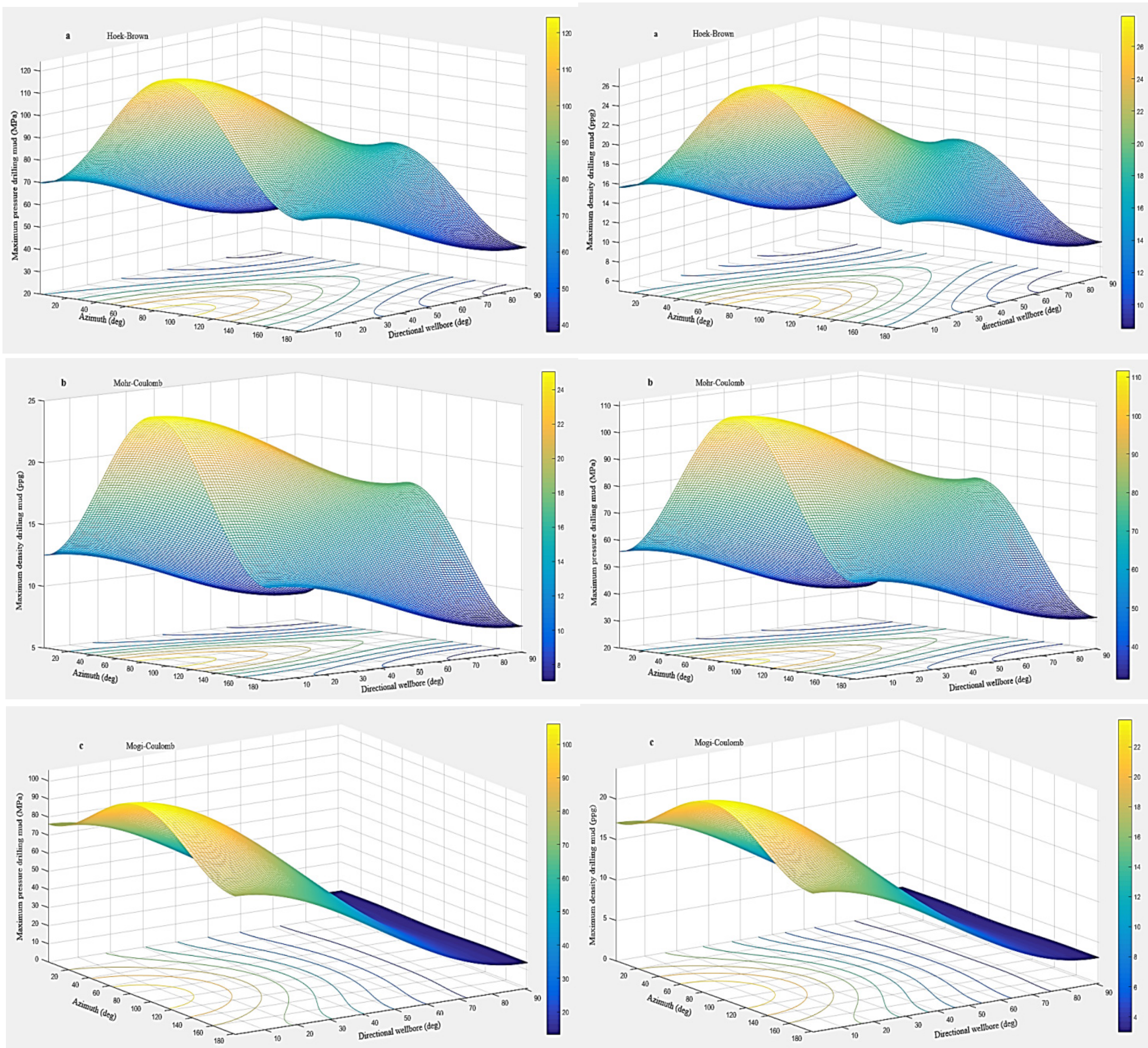

Figure 2. Maximum pressure and the mud weight requirements based on azimuth and wellbore angle deviation using a) Hoek-Brown, b) Mohr-Coulomb and c) Mogi-Coulomb.

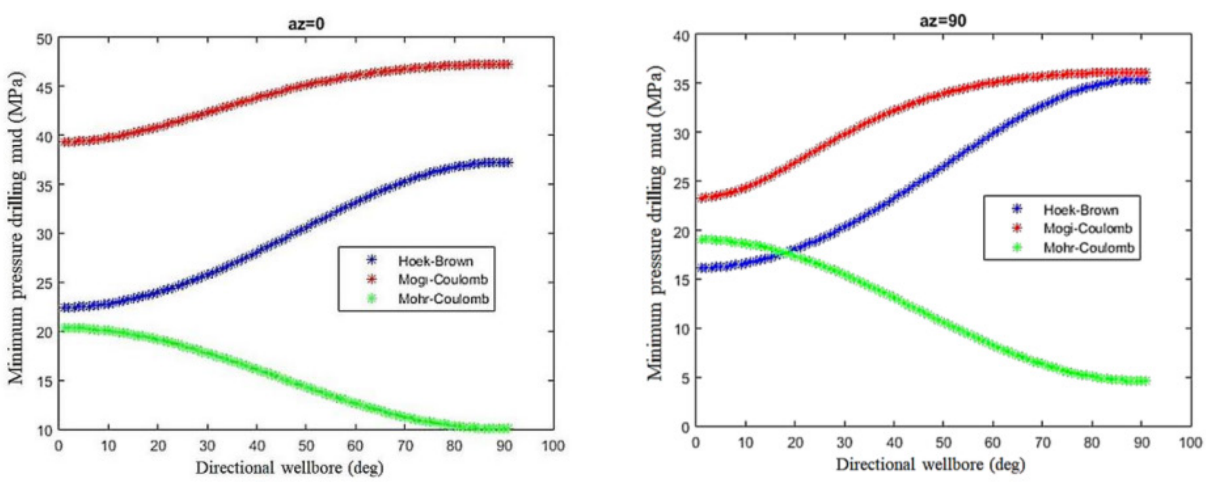

Figure 3. Minimum drilling mud pressure is predicted at 0 and 90 degrees azimuths.

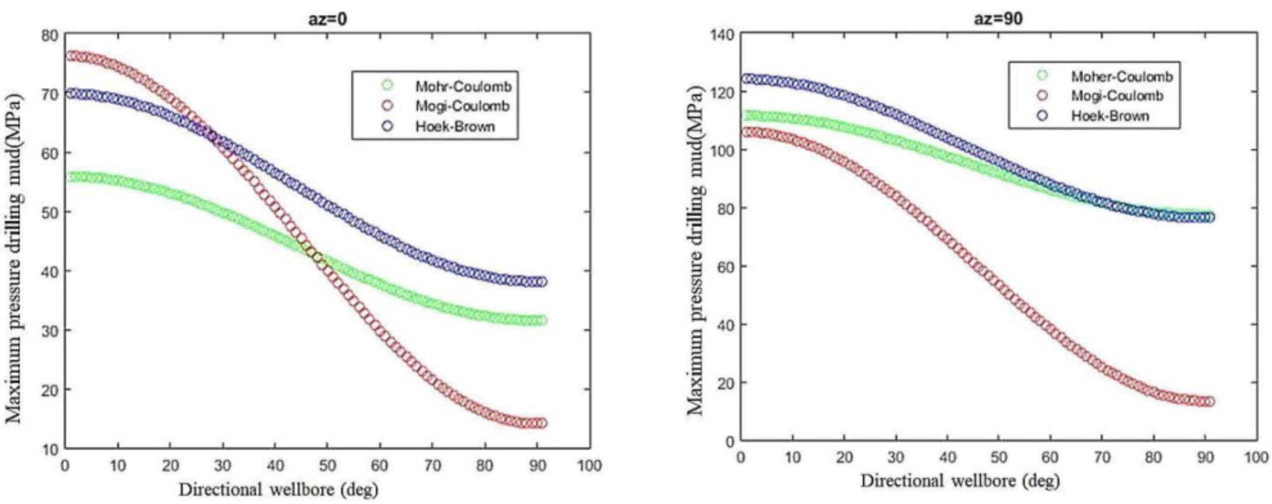

Figure 4. Maximum drilling mud pressure is predicted at 0 and 90 degrees azimuths.

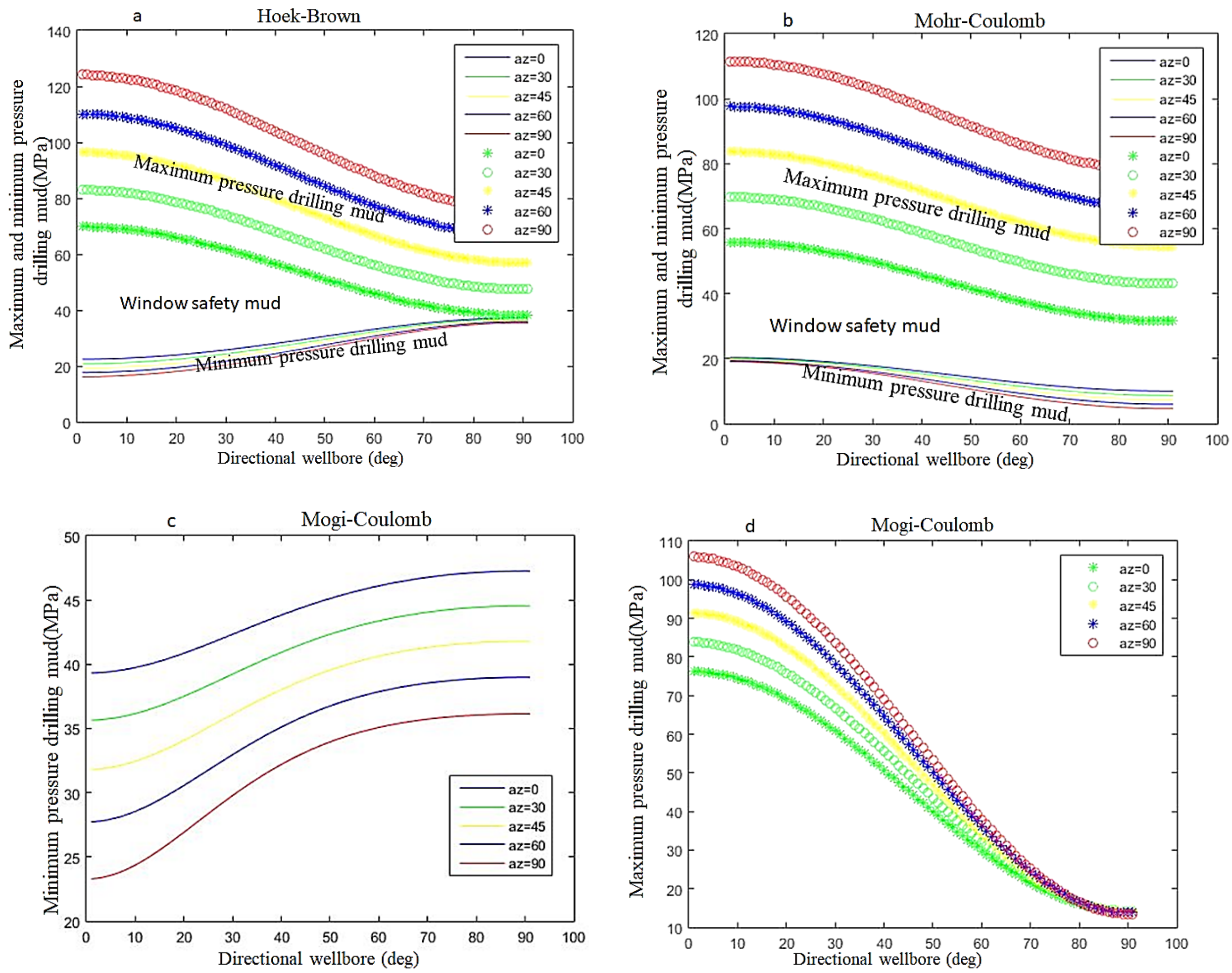

Figure 5. Safety mud window drilling pressure requirements based on azimuth and wellbore angle deviation using a) Hoek-Brown, b) Mohr-Coulomb, c and d) Mogi-Coulomb.

least. The Hoek-Brown criterion predicts the minimum pressure and the weight of the drilling mud more than Mohr-Coulomb and less than the Mogi-Coulomb and approaches the Mogi-Coulomb scale by increasing the angle of the deviation. By using the Mogi-Coulomb criterion, in the vertical state, the minimum pressure of the predicted mud weight was 39.33 (MPa) and 28.93 (PCF), respectively. This value is 0.492 (PCF) less than the actual value, and the reason why it is less than the drilling mud pressure that in the field can be applied is that the safety pressure is usually considered to be 150 (psi) to 200 (psi) higher than the pressure applied to the field, they are.

The reason for the difference between the Mogi-Coulomb criteria with both the Hoek-Brown and the Mohr-Coulomb criterion is that the Mogi-Coulomb criterion, considers medium and intermediate stresses for determining the trajectory, pressure, and mud weight. Therefore, the predicted rock resistance using Mogi-Coulomb is closer to the actual field value. As a result, the predicted mud pressure by Mogi-Coulomb to keep the wellbore stability is more than the values predicted by the Mohr-Coulomb and Hoek-Brown criteria. Thus, the Mogi-Coulomb criterion is more realistic and more conservative in the wellbore stability analysis. In contrast to the Mohr-Coulomb and Hoek-Brown criteria, only minimum and maximum stresses, as well as the Mohr-Coulomb tensile strength and the Hoek-Brown criterion, consider single-axial compressive strength of rock and assume that moderate stress has no effect on rock resistance As a result, the predicted rock resistance is less than the actual rock resistance. Therefore, the Mohr-Coulomb and Hoek-Brown criteria predict a minimum pressure drop for the wellbore wall. The Hoek-Brown criterion for predicting single-axial compressive strength predicts a minimum amount of drilling and weight mud compared to the Mohr-Coulomb criterion. In summary, the minimum and maximum predicted fluctuation pressure is given by three criteria at a depth of 3791 (m) in Tables 3 and 4.

The safety window and the optimum drilling mud are a range of drilling mud pressures that, if the pressure is low, shear failure wellbore, and if the pressure is higher than this range, the tensile fracture occurs in the wellbore.

Figure 6 shows the radial and tangential stresses around the wellbore. These stresses are not affected in a 6-radius wellbore ($\sigma_\Theta - \sigma_r = 0$). Increasing pressure and hydraulic weight of drilling fluid (drilling mud), causes increased radial stress and decreased tangential stress. Also, decreased deferent two stress and this deferent stresses caused more stable wellbore.

Table 3. Comparison of three rock failure criteria in the vertical wellbore.

Rock failure criteria	Predicted minimum mud pressure (MPa)	Predicted maximum mud pressure (MPa)
Hoek-Brown	29.43	69.86
Mohr-Coulomb	24.34	55.87
Mogi-Coulomb	39.33	76.24

Table 4. Comparison of three rock failure criteria in the horizontal wellbore.

Rock failure criteria	Predicted minimum mud pressure (MPa)	Predicted maximum mud pressure (MPa)
Hoek-Brown	37.26	38.09
Mohr-Coulomb	24.03	31.56
Mogi-Coulomb	47.27	56.4

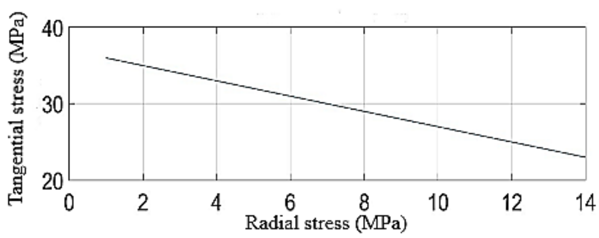

Figure 6. The radial and tangential stresses around the wellbore.

Figure 7 shows the maximum and minimum pressure of drilling mud that takes the shear stress to zero and applies the main stresses 1, 2, and 3 showing the angle of deviation of the well. By increasing the deflection angle, the maximum drilling mud pressure decreases. And the minimum mud pressure, should be increased by increasing the deflection angle of the well, but due to the proximity of stresses main 2 and 3 to each other minimum drilling mud pressure decrease with increasing deflection angle and sub-equilibrium drilling from angle deviation of 30 degrees to the horizontal position is difficult and not recommended; Because the minimum flower pressure is close to or smaller than The pressure is porous. Therefore, the closer the maximum horizontal stress is to the vertical stress, the range of the flower safety window drilling is larger and wider, and conversely, the farther the horizontal stress is from the maximum vertical stress. In other words, if the maximum the closer the horizontal stress is to the minimum horizontal stress, the smaller and more limited the safety range of the drilling mud.

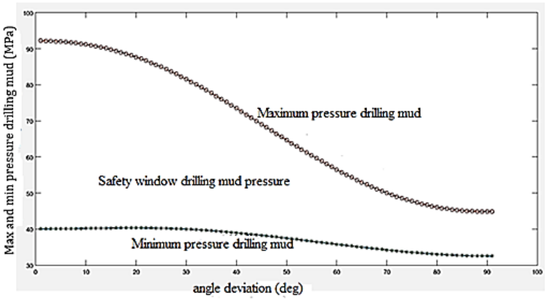

Figure 7. Changing the mud safety window according to the angle of deviation of the well by applying stresses.

According to the Mogi-Coulomb standard tables, the highest pressure and weight of drilling mud are predicted, but according to the drilling mud pressure drilling in this field, which was carried out at a pressure of 40 MPa and no instability was reported. The Mogi-Coulomb criterion is therefore the best failure and more conservative criterion and is recommended for drilling operations and this can be due to the average and medium stress used in this criterion.

5. Analysis of Wellbore Stability Using Boundary Elimination Method

Figure 8 shows the model geometry that the dimensions of the model are 1.5 × 1.5 m and the border elimination is 40 40 40 and the radius is 0.1 m.

The next step is to select the model and apply the properties of the materials. In this model, there are two criteria for Mohr-Coulomb failure Hoek-Brown is used to study the behavior of the rock and determine the stress around the well and the safety factor.

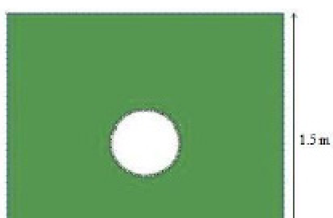

Figure 8. The model geometry that the dimensions of the model are 1.5 × 1.5 m and the border elimination is 40 40 40 and the radius is 0.1 m.

In this model, initially, the vertical stress at a depth of 3791 meters is equal to 96.7 MPa, which is perpendicular to the axis of the well (vertical well) have been. Also, the maximum horizontal stress was equal to 59.4 MPa along the x-axis, and the minimum horizontal stress equal to it was 44.5 MPa along the y-axis. The created well with a diameter of 0.2 m is subjected to internal pressure Pw and then the stability of the horizontal well in the direction of minimum and maximum horizontal stress is analyzed.

Using Examine 2D software, wall displacements, main stresses, mean, safety factor and other parameters required for well stability analysis can be examined. In this study, the wall stability well has been inspected based on safety factors.

Figure 9 shows the safety factor for different pressures applied to the inner wall of a vertical well. These images were created by applying the Hoek-Brown refractive index parameters with zero wellbore wall internal pressure.

Shear failure occurs and causes internal collapse due to increasing internal pressure. The pressure of 31 MPa is stabilized in the wellbore wall which enters the threshold of the drilling fluid safety window and until pressure is applied 56 MPa reaches the end of this window and at a pressure of 57 MPa, small cracks begin to form in the wall. Further increase in internal pressure (for example, 100 MPa) causes tensile failure in the wall and ultimately waste drilling fluid and well wall instability occurs. So the mud window safety window that failed this criterion comes in a pressure range of at least 31 MPa and a maximum of 56 MPa.

Figure 10 shows the safety factor for different pressures applied to the inner wall of a vertical well. These images were created by applying the Mohr-Columbus refractive index parameters with zero wellbore wall internal pressure. Shear failure occurs and causes internal collapse due to increasing internal pressure; so in Pressure of 25 MPa stabilized well wall that enters the threshold of the drilling fluid safety window and until pressure is applied 61 MPa reaches the end of this window and at a pressure of 62 MPa, small cracks begin to form in the wall.

Further increase in internal pressure (for example, 100 MPa) causes tensile failure in the wall and ultimately wastes drilling fluid, and wellbore wall instability occurs. So the mud window safety window failed this criterion. It comes in a pressure range of at least 25 MPa and a maximum of 61 MPa.

Figure 11 shows the safety factor for different pressures applied to the inner wall of a horizontal wellbore. These images were created by applying the Hoek-Brown refractive index parameters. At a pressure of 46 MPa, the wellbore wall is stable, indicating the entrance to the threshold of the drilling mud safety window, and at a pressure of 50 MPa, this window ends Finds. At pressures higher than this amount, small cracks are created in the wall and further increase the internal pressure it causing tensile failure in the wall, which ultimately causes drilling fluid waste and instability of the wellbore wall.

The drilling fluid safety window obtained from this failure criterion for the model has a compression range of

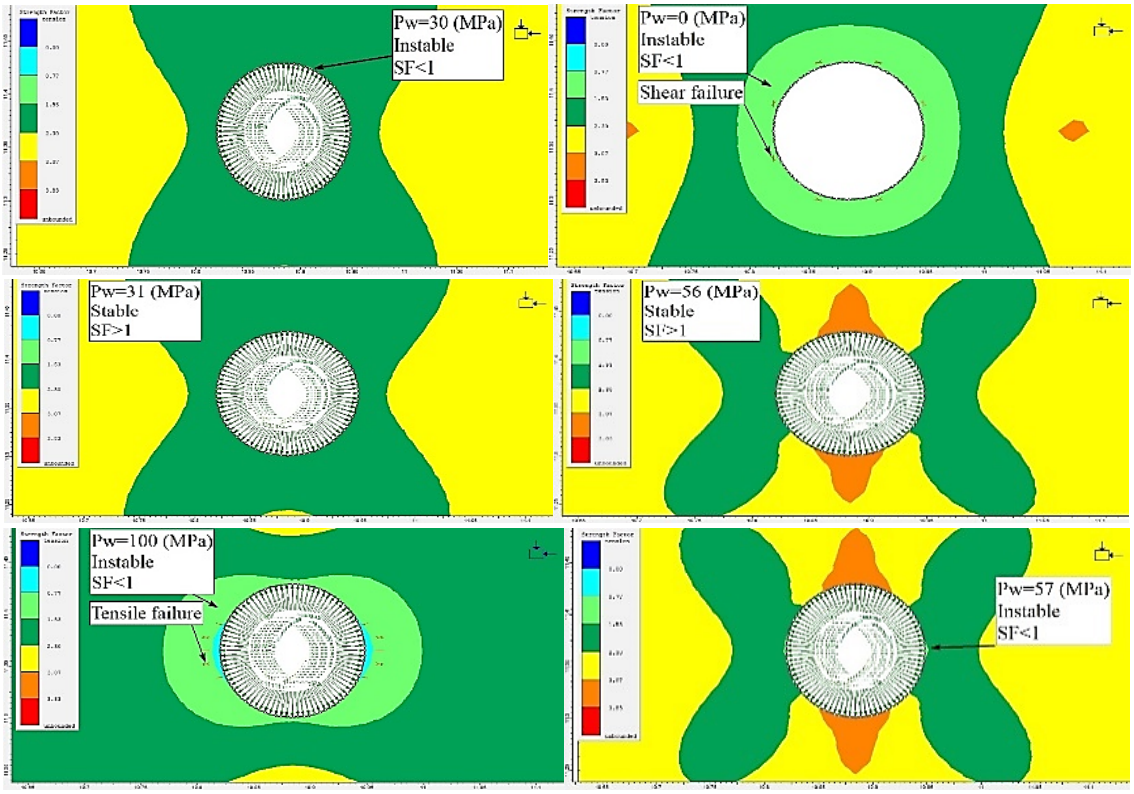

Figure 9. Changes in the safety factor of drilling fluid by applying different internal pressures to the wall of the vertical well (Hoek-Brown).

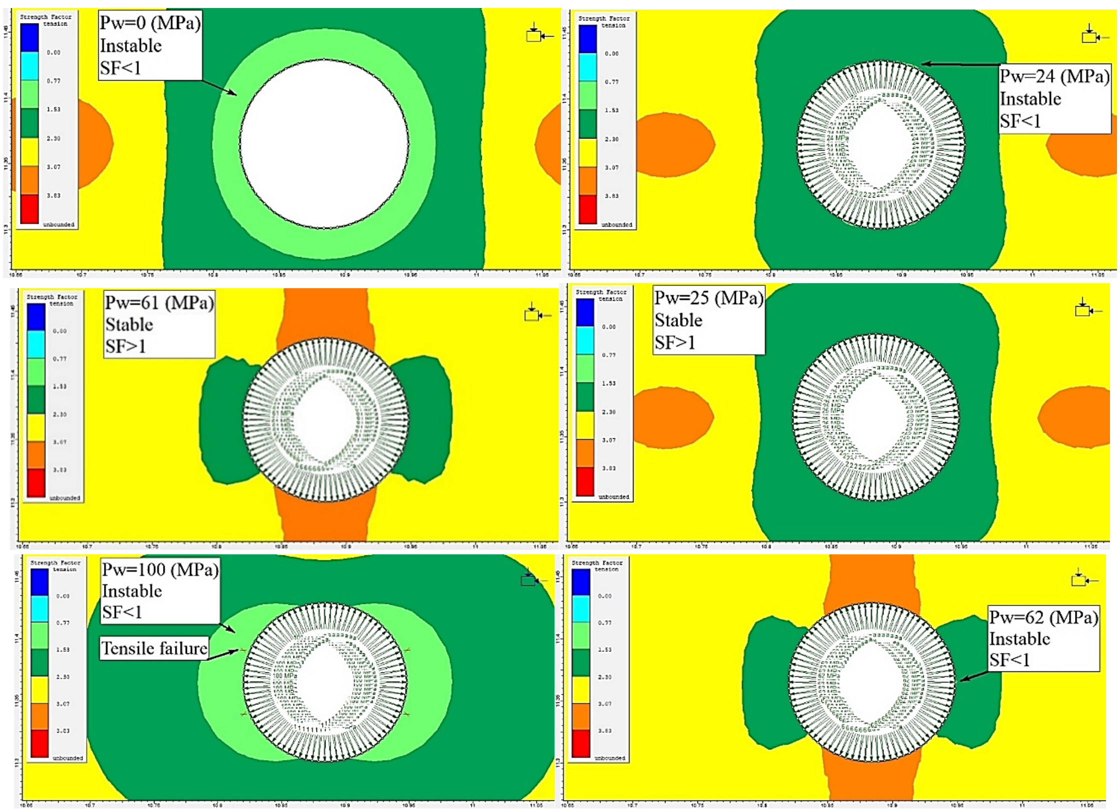

Figure 10. Changes in the safety factor of drilling fluid by applying different internal pressures to the wall of the vertical well (Mohr-Coulomb).

at least 46 to 50 MPa.

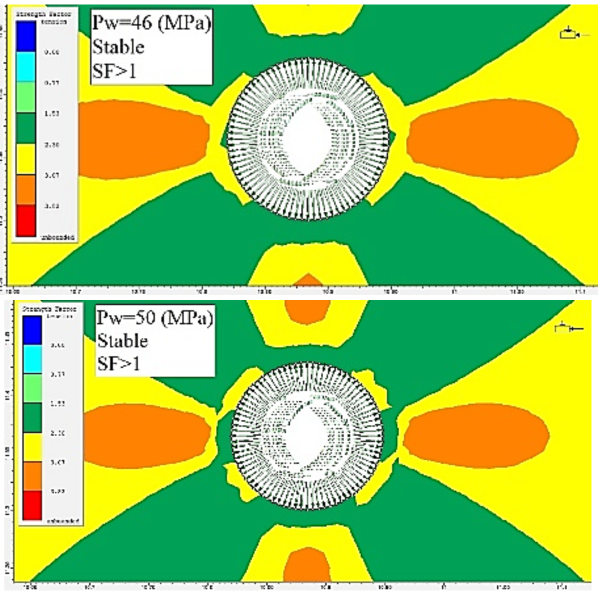

Figure 11. Changes in the drilling fluid safety factor by applying different internal pressures to the horizontal well wall (Hoek-Brown).

Figure 12 shows the safety factor for different pressures applied to the inner wall of a horizontal wellbore. These images were created by applying the Mohr-Columbus refractive index parameters. At a pressure of 43 MPa, the wellbore wall stabilized, which indicates the entrance to the drilling mud safety window threshold, and up to a pressure of 57.5 MPa.

The window continues and at higher pressures, small cracks appear in the wellbore wall. Further increase of internal pressure causes tensile failure in the wellbore wall and ultimately causes drilling fluid waste and instability of the wellbore wall; so the drilling fluid safety window obtained from this failure criterion for the model has a compression range of at least 43 MPa and a maximum of 57.5 MPa.

Figure 13 shows the internal wall pressure at a depth of 3791 m, 200 psi greater than the pore pressure for both criteria was applied and the result was that in the vertical well drilled in the direction of vertical stress, the stability of the wellbore wall with a safety factor above one were observed; But by drilling horizontal wells in the direction of minimum and maximum horizontal stresses, well wall instability and safety factor below one was observed. Horizontal wellbore instability in the direction of maximum horizontal stress. The instability of the horizontal well in the direction of horizontal stress is minimal, which is due to the vertical stress in the direction perpendicular to the wall.

Finally, the results of the two failure criteria in the vertical and horizontal positions are given in Tables 5 and 6. In Table 5, the safety factor for the internal wall pressure is 200 psi more than the pore space, in which the vertical wellbore wall pressure is stable for both criteria, but in the horizontal wellbore, the wellbore wall is unstable. The internal wellbore pressure is 200 psi more than the pore pressure, in which the vertical wellbore wall is stable for both criteria, but in the horizontal wellbore, the wellbore wall is unstable. Table 6 shows the drilling mud pressure safety factor for both rock failure criteria for vertical and horizontal wellbores. The Mohr-Coulomb failure criterion for vertical and horizontal conditions shows that this range is more than Hoek-Brown.

Table 6 shows the drilling mud pressure safety window range for both failure criteria for vertical and horizontal wells. The Mohr-Coulomb failure criterion for vertical and horizontal conditions shows that this range is more than Hoek-Brown.

By studying Tables 5 and 6, it is clear that the stability of the wellbore in the vertical position is better than in the horizontal position and vertical drilling will have a higher safety factor. In this study, due to the limitations of Examine 2D software, the stability analysis of sloping wells was not prepared and only analyses are made in both vertical and horizontal directions. The results from the analytical method showed the failure criterion indicated that the obtained results are reliable.

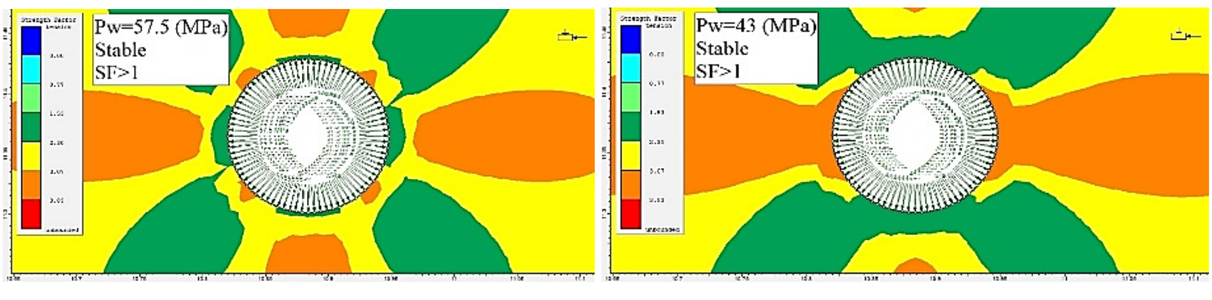

Figure 12. Changes in the safety factor of drilling fluid by applying different internal pressures to the horizontal wellbore wall (Mohr-Coulomb).

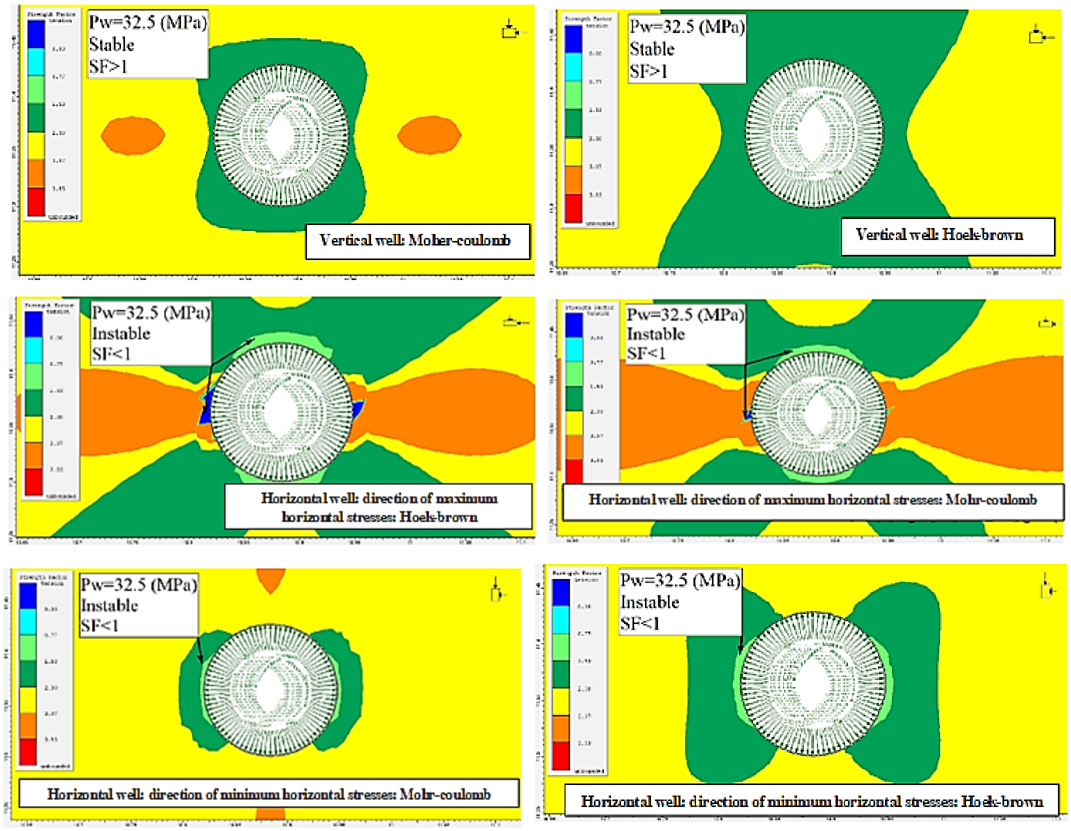

Figure 13. Safety factor changes in horizontal and vertical wells at an internal pressure of 32.5 MPa.

Table 5. Comparison of the safety factor of two failure criteria in vertical and horizontal wells at an internal pressure of 32.5 MPa.

Rock failure criteria	Mud pressure wellbore (MPa)	Safety factors for a vertical well	Safety factors for horizontal well
Hoek-Brown	32.5	SF > 1	SF < 1
Mohr-Coulomb	32.5	SF > 1	SF < 1

Table 6. Comparison of drilling mud pressure safety window with two failure criteria in vertical and horizontal wells.

Rock failure criteria	Drilling mud pressure safety window in vertical well (MPa)	Drilling mud pressure safety window in horizontal well (MPa)
Hoek-Brown	31-56	46-50
Mohr-Coulomb	25-61	43-57.5

6. Conclusions

We compared three criteria. Based on the presented graphs, the Mogi-Coulomb criterion provides a better result than other criteria, which can be due to the application of the main intermediate stress σ2. The Mohr-Coulomb criterion predicts, concerning the tensile strength, a smaller minimum pressure for the mud when increasing the angle deviation of the well. According to the presented diagrams, the effect of the azimuth of the well on the lower angles is significant, but with increasing the angle of the deviation, its effect is reduced. The angle of deviation plays the most significant role in the stability of the wellbore. The lower boundary of the safety of the mud is greater than the permeate pressure and the upper boundary exceeds the horizontal maximum tensile, however, these change with the angle and azimuth. The mud weight caused a higher pressure than the pore pressure and prevented the blowout of the well, but the weak formation causes tensile fractures in the wellbore wall and the loss of fluidity. To understand why the drilling direction is so important it should note that at the depth of interest there is a significant difference between the maximum and minimum horizontal principal stresses. Thus, the instability of the wellbore wall is due to the increase in the difference in wellbore stresses. To prevent this issue, increasing the hydrostatic pressure of the drilling fluid increases the radial stress and decreases the tangential stress, and this reduces the difference between the tangential and radial stresses of the wellbore and makes the wellbore more stable. By drilling a wellbore, the stress regime is perturbed around the wellbore wall, and the highest concentration of stress and displacement will occur. To control such occurrences the bottom hole pressure should be optimized and so designed to prevent the instability resulting from stress concentration and wellbore displacement and sand production.

Author Contributions

Faramarz Abazari: Wrote the paper; Hossein Jalilifar: Contributed data and analysis tools; Mohammad Ali Riahi: Conceived and designed the analysis.

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Data Availability Statement

Restrictions apply to the availability of these data. Data were obtained from the National Iranian Oil Company and are available [from the authors at faramarz880761001@yahoo.com] with the permission of the National Iranian Oil Company.

Conflict of Interest

Author declares that there is no conflict of interest.

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