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Application of Geomechanical Modeling and Determination of Optimal Rock Fracture Criteria in the Design of Mud Weight in One of the Southern Iraq Oil Fields

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ABSTRACT

The stability of the wellbore wall is one of the most crucial issues during drilling oil and gas wells. To avoid wellbore instability, determining a safe mud weight window for minimizing the risk of drilling mud loss/lost circulation and wellbore blowout is essential. If it is calculated accurately, the well drilling will be carried out safely and at a higher speed. In line with achieving these goals, Flac3D software was employed to design a proper mud weight during the drilling operation. In this regard, different zones of a southern Iraq oil field were investigated, and the effect of mud weight on wellbore wall stability was examined. The results of modeling indicated that the minimum mud weight in Zone 1 is 5.70 lb/gal, resulting in safe drilling without wellbore wall collapse. The maximum displacements in the X and Y directions in this zone are 0.3621 and 0.8445 mm, respectively. The minimum mud weight in Zone 2 leading to wellbore stability was found to be 6.61 lb/gal, with maximum displacements in X and Y directions limited to 0.2448 and 0.6614 mm, respectively. In Zone 3, the minimum mud weight for safe drilling was found to be 7.43 lb/gal, the highest value compared to other zones, with maximum displacements in the X and Y directions both limited to 0.059 mm. The minimum mud weight for safe drilling was found to be 6.51 lb/gal in Zone 4 and 5.05 lb/gal in Zone 5. The maximum displacements in the X and Y directions are both 0.0848 mm in Zone 4 and 0.291 mm in Zone 5. Thus, the minimum mud weight for maintaining wellbore stability and safe drilling in the whole oil field is 7.43 lb/gal. Considering 7.43 lb/gal as the optimum mud weight in all formations, the drilling mud pressure is consistently smaller than the corresponding pore pressure at all target depths, indicating that the drilling operation is under-balanced in this oil field.

KEYWORDS

Wellbore stability, Geomechanical modeling, Drilling optimization, Safe mud weight window, Oil field

I. INTRODUCTION

One of the most important problems associated with oil fields is the failure of casings while drilling, reservoir compaction, excess pore pressure and compaction, sand production, fault activity, and ground settlement. The above factors result in wellbore wall instability, imposing massive costs on petroleum companies. The stability of the wellbore wall and drilling string is one of the most paramount and fundamental issues during drilling oil and gas wells. Hence, the use of tools and methods of geomechanical simulation and modeling for determining the stability and design of an optimal drilling trajectory is necessary .

To achieve the target of wellbore wall stability, determining a safe mud weight window for minimizing the danger of drilling mud loss and decreasing well blowout is extremely crucial. If it is calculated accurately, the well drilling will be carried out safely and at a higher speed. In other words, by geomechanical modeling through the determination of the safe mud weight value, the concern of wellbore wall stability will be addressed sufficiently. Besides, in many oil wells existing in naturally fractured carbonate reservoirs, the determination of the accurate mud weight is performed for the sake of stabilizing the wellbore wall, preventing the entry of formation waters to the wellbore, and reducing drilling mud loss. For this reason, the drilling mud pressure and its weights are increased to prohibit damage to the wellbore wall and to prevent well blowout. However, an excessive rise in mud weight may lead to a tensile failure. Therefore, drilling engineers have to consider the safe drilling mud weight to diminish stress concentration and prevent formation failure. Mohr-Coulomb and Mogi-Coulomb failure criteria are among the most commonly used methods to determine the safe drilling mud window. In the past, the Mohr-Coulomb failure criterion was utilized along with Kirsch equations to determine the safe drilling mud

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window. Recent investigations have indicated that the selection of plastic analysis-based criteria has more compatibility in geological formations. Furthermore, many scholars have suggested the use of elastoplastic theories for the study of wellbore wall stability (Fang et al., 2023; Guerrero et al., 2020; Wang et al., 2022; Yang et al., 2022). Hence, making a correct decision for drilling a well in the accurate direction of geomechanical stresses is essential. Thus, to obtain and accurately determine the principal stresses of the wellbore wall, numerical simulation methods are very helpful. That is, through the application of formation geomechanical modeling and obtained data from a well in an oil field, the direction of principal stresses can be determined. Finally, using this procedure, the accurate drilling program can be determined for other wells of the oil field that are being planned (Tran et al., 2022; Kanfar et al., 2015, Kim et al., 2022; Wang et al., 2015).

Al-Qahtani and Zillur (2001) performed geomechanical modeling of the Ghawar oil field in Saudi Arabia using mathematical algorithms. In the algorithm used, the mechanical properties of the rock and the magnitude of in-situ stress were calculated using shear and compressional wave transit times. They calibrated the results obtained from the geomechanical modeling with laboratory data and proved that the magnitude of vertical stress can also be a function of Young's modulus. Mohiuddin et al. (2001) studied wellbore stability in a sandstone reservoir in Saudi Arabia using statistical analyses and geomechanical modeling. The results showed that the main cause of wellbore instability in the studied field was low drilling mud weight, and by accurately predicting the safe mud weight window, they extended it for the entire field development. Al-Ruwaili and Chardac (2003) presented relationships between the geomechanical and geological properties of the Ghawar oil field in Saudi Arabia using three-dimensional geomechanical modeling. They used existing well logs and seismic data for geological and geomechanical modeling. The most significant weakness of their research was the lack of validation of the values achieved through numerical modeling. Ahmed et al (2007) used geomechanical modeling and considered initial stresses to determine the drilling direction of gas wells in a Saudi Arabian gas field. In this study, considering that the location of wellbore breakouts was related to the wellbore trajectory as well as the stresses on the wellbore wall, they estimated the effective strength of the wellbore wall formations by identifying and differentiating wellbore breakouts and calculating the applied stresses using a stress polygon. Al-Wardy and Urdaneta (2010) investigated wellbore instability in the unstable shale formations of the Nahr Umr in Oman using geomechanical modeling. Using this approach, they presented the minimum mud weight and the uniaxial compressive strength required for wellbore stability to prevent wellbore failure at different inclinations and azimuths. Abalioglu et al. (2011) addressed the problems associated with drilling and wellbore instability in the oil fields of northern Iraq by estimating the mechanical properties of the formation and the applied stresses, and through geomechanical modeling of the formation. Finally, they estimated the locations of wellbore breakouts using caliper logs for calibration. Qiuguo et al. (2013) investigated wellbore stability in one of the oil fields in Oman using 3D geomechanical modeling. The 3D geomechanical modeling was used to estimate the maximum stress required for hydraulic fracturing, wellbore stability, and fracture stimulation in horizontal wells. The results indicated that the main cause of wellbore instability was the low safe mud weight in the drilling direction, as well as the shear failure of the formation. Mohammed et al. (2018) analyzed wellbore instability for the Nahr Umr Formation in southern Iraq. Data from more than twenty wells (vertical and deviated wells) were examined to identify the main factors controlling instability problems and to design an optimal mud window. Based on data from density logs, gamma ray logs, sonic logs, formation micro image logs, and resistivity logs, they estimated the magnitude and direction of the in-situ principal stresses, pore pressure, and rock mechanical properties. The constructed geomechanical model was evaluated with three failure criteria: Mohr-Coulomb, Modified Lade, and Mogi-Coulomb, and the appropriate mud weight for drilling in each well was determined. The results of the evaluations and geomechanical modeling demonstrated that most wellbore instability problems are primarily due to rock failure around the wellbore due to high stresses and low rock strength, as well as improper drilling operations. Bagheri et al. (2021) used a 1D geomechanical model to investigate failure mechanisms and estimate the safe mud weight window using the Mohr-Coulomb failure criterion. Using density and sonic logs, acoustic impedance (AI) and reflection coefficient (RC) were determined. The combination of layers using artificial intelligence identified different positive and negative values for RC and shear failure-prone areas, and the mud weight in these areas was analyzed according to the interpretation of AI and RC values and the obtained results. In the constructed geomechanical model, areas with approximately constant AI log values and near-zero values for the RC log were homogeneously stable in terms of lithology. However, they had a lower tensile failure threshold than shear failure-sensitive intervals. Therefore, if the mud weight is increased, these are areas prone to failure or tensile failure. Hoseinpour and Riahi (2022) investigated the geomechanical parameters of one of Iran's hydrocarbon reservoirs to determine the mud weight window, optimal drilling trajectory, and wellbore stability. The optimal drilling mud weight windows and safe drilling deviation trajectories were investigated using geomechanical parameters. To estimate safe drilling trajectories, the parameters of Poisson's ratio, Young's modulus, and unconfined/uniaxial compressive strength were determined. The results suggested that the maximum horizontal stress and Poisson's ratio have the greatest impact on determining the optimal drilling mud weight and safe drilling deviation trajectories. In contrast, vertical stress and Young's modulus have the least impact on drilling mud weight windows and safe drilling deviation trajectories.

In this research, the application of geomechanical modeling and determination of the optimal rock failure criteria have been used in the design of the safe wellbore trajectory in one of the southern Iraq oil fields. Having determined the stresses, the suitable drilling mud weight was calculated via numerical techniques of FLAC3D. Since the wells of a given reservoir do not usually behave substantially differently in terms of geomechanical properties, the optimal determined mud weight may be generalized to other wells of the reservoir to prevent blowout and unwanted fracturing. It is also possible to employ this geomechanical information as the base information for the hydraulic fracturing process during improved oil recovery. Recently, in developing countries such as Iraq having huge oil reservoirs, the change ranges of drilling operation factors are determined by drilling engineers using well-established empirical models. The results obtained in this study can be employed to identify influencing and operational factors of drilling according to formation geomechanical properties. Such investigations have not been conducted sufficiently in Iraq. Therefore, the applied investigations using geomechanical modeling of the wellbore and its generalization to the oil field can help shed light on a more realistic understanding of the wellbore stability phenomenon during a drilling operation. The objectives of this study were as follows: 1) determining the minimum drilling mud pressure in different zones of the studied oil field and in the whole oil field; 2) investigating the drilling type in the oil field.

II. GOVERNING EQUATIONS

Through governing equations of geomechanical parameters and in situ stresses, the safe drilling mud window is determined for one of the wells existing in the oil field. These relationships are empirical and have applications in the calculation and evaluation of elastic parameters. The magnitude of geomechanical properties such as Young's modulus of elasticity or uniaxial compressive strength directly affects the ability of the wellbore wall rocks to carry the applied stresses and to tolerate the stress concentrations without undergoing significant plastic deformation or failure. Therefore, the higher values of the above-mentioned parameters will lead to a stronger wellbore wall and so will result in a higher degree of wellbore stability.

The following equations (Eqs. 1-18), all existing in (2024), are utilized to evaluate the geomechanical parameters:

$$Y_{static} = 0.541 \times \mathrm{Y_{Dynamic}} + 12.852 \tag{1}$$

Y_{static} denotes static Young's modulus, and $\mathrm{Y_{Dynamic}}$ stands for dynamic Young's modulus.

$$UCS = 2.65 \times \frac{Y_{STATIC}^{\frac{1+2\times Biot}{2}}}{\propto^{\frac{1+2\times Biot}{2}}} \tag{2}$$

UCS represents the uniaxial compressive strength, Biot symbolizes Biot's coefficient, and $\propto$ indicates the porosity value of the formation.

$$\propto = 49.03 - 1.26 \times (\varphi \times 100) \tag{3}$$

The parameter φ is the internal friction angle of the rock.

The geomechanical parameters are calculated in shale formations using the following equations:

$$Y_{\mathrm{static}} = 0.428 \times Y_{Dynamic}^2 + 0.2334 \times Y_{Dynamic} \tag{4}$$

$$UCS = 10 \times \frac{304.8}{DT - 1} \tag{5}$$

$Y_{Dynamic}$ is obtained by using dynamic shear modulus, and bulk modulus and these two dynamic moduli are estimated via the transit time of shear and compressive waves and the bulk density. DT signifies the slowness of compressional sonic wave obtained using a cross-dipole sonic log.

$$\varphi = \mathrm{Asin}\left(\frac{VP - 1000}{VP + 1000}\right) \tag{6}$$

VP represents the velocity of the compressional wave.

To evaluate static Poison's ratio and Gassman's Biot, the following relations are employed:

$$POIS_{Static} = C1 \times POIS_{Dynamic} + C2 \tag{7}$$

Since Poison's coefficient for isotropic linear elastic materials is between -1 to 0.5, and for most rocks it is between 0 to 0.5, the constant values of $C1$ and $C2$ are assumed as default values of 0.8 and 0, respectively.

$$BIOTGASSMAN: 1 - \frac{(K\ MOD\ DRY)}{(K\ MOD\ MIN)} \tag{8}$$

The dynamic Poison's ratio is evaluated through Eq. (9) using the transit time of compressional and shear waves.

$$\vartheta = \frac{\frac{1}{2} \times (DTS/DTC)^2 - 1}{(DTS/DTC)^2 - 1} \tag{9}$$

Cohesion is computed based on the Mohr-Coulomb criterion as follows:

$$C = UCS \times (1 - sin\varphi/2cos\varphi) \tag{10}$$

Pore pressure is predicted according to Eaton's equation as follows:

$$P_p = S_v - (S_v - P_{pn}) \times (\frac{DTC_n}{DTC})^3 \tag{11}$$

DTC_n and DTC are respectively transit time/slowness of the compressional wave in shale in normal pressure and that obtained using the acoustic log. P_{pn} is the normal hydrostatic pore pressure.

Drilling-induced stresses are usually higher than the initial stresses, and if they are larger than the rock strength, drilling-induced fractures will generate in the reservoir rock. They are calculated using the following equations:

$$\sigma_z = S_v - 2\vartheta(S_{H\,max} - S_{h\,min})\cos 2\theta \quad (12)$$

$$\sigma_\theta = (S_{H\,max} - S_{h\,min}) - 2(S_{H\,max} - S_{h\,min})\cos 2\theta - P_w \quad (13)$$

$$\sigma_r = P_w \quad (14)$$

$$P_{w(BO)} = \frac{[A - UCS - P_p(q-1)]}{1+q} \quad (15)$$

$$P_{w(Break)} = \frac{[UCS + P_p(q-1) + qD]}{1+q} \quad (16)$$

$$q = (1+\sin\varphi)/(1-\sin\varphi) \quad (17)$$

$$A = 3\sigma_h - \sigma_H\ ,\ D = 3\sigma_H - \sigma_h \quad (18)$$

$P_{w(BO)}$ and $P_{w(Break)}$, which respectively stand for collapse and fracturing pressure of the formation, are considered equal to the low and high limits of mud pressure (i.e., the safe drilling mud window). θ is the angle measured clockwise relative to the maximum horizontal stress .

III. Research Methodology

The methodology of this research was as follows:

1. Investigating the structural geology of the target oil field in southern Iraq;
2. Building an appropriate geomechanical model for one of the wells of this oil field;
3. Using empirical relationships and well logging data (especially acoustic log data) for creating the geomechanical model;
4. Modeling stress, pore pressure changes, and wellbore wall stability using numerical simulation;
5. Determining the safe mud window through Mohr-Coulomb and Mogi-Coulomb failure criteria.
6. Validating the results obtained for petrophysical and mechanical parameters (especially pore pressure) by using daily drilling reports and previous investigations.

Since geomechanical investigations are not usually highly case-dependent unless there are significant heterogeneities and geological differences in the target oil fields/reservoirs, the research method adopted in this research may be generalized for other oil fields/reservoirs with similar geological settings.

IV. Target Oil Field

The target oil field is one of the southern Iraq oil fields. This field was discovered in 1953 with about 17 billion barrels of original oil in place. The size of the oil field is approximately 38 km × 12 km. Fig. 1 shows the geographical position of the field. API of oil in this field is equal to 34 .

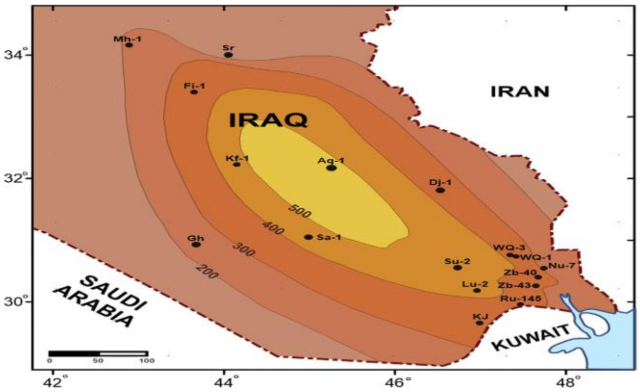

Fig. 1. Geographical position of the target oil field

This sandstone field possesses different geological layers. The geological layers in this field are composed of five oil zones and 15 layers. The recovery factor for this oil field has been low (less than 15%), and the rate of oil production has been decreasing. Water oil contact in this field is in the approximate depth range of 3250-3294 m .

Reservoir and elastic properties of reservoir rock, Mohr-Coulomb parameters, and in situ stresses are presented in Table 1, which includes porosity, permeability, pore pressure, and Biot's module in different formations of the field.

Table 1. Reservoir and elastic properties of reservoir rock, Mohr-Coulomb parameters, and in situ stresses in different zones of the field

Formation	Depth (m)	Porosity (%)	Pore pressure (MPa)	Permeability (mD)	Biot module	Bulk modulus (GPa)	Shear modulus (GPa)	Poisson ratio
1	3810	3.72	46.1	20	0.65	15.78	8.26	0.28
2	3945	2.3	47.7	22	0.6	14.25	7.99	0.26
3	3956	4.9	47.7	49	0.7	21.25	11.78	0.27
4	4070	5	47.5	2	0.7	25.1	12.54	0.29
5	4130	2.63	47	13	0.6	19.64	9.33	0.29

Formation	Young modulus (GPa)	Vertical stress (MPa)	Maximum horizontal stress (MPa)	Minimum horizontal stress (MPa)	Internal friction angle (degree)	Cohesion (MPa)	Tensile strength (MPa)
1	21.1	109.4	74.2	57.4	35.2	3.1	8.8
2	20.2	112.9	74.8	58.5	40	3.2	9.6
3	29.8	113.2	77	52.9	41.5	2.6	12
4	32.2	116.2	80.6	55	42.2	3	12
5	24.2	117.8	80.7	61.6	117.8	3.8	11.3

V. DATA ANALYSIS

A. *Wellbore Stability Modeling in Zone/Formation 1*

Fig. 2 exhibits the yield zone in Formation 1 using a drilling mud with an equivalent weight of 4.46 lb/gal. Table 2 presents the results obtained from the calculation of this parameter using different mud weights. As observed, mud weight values range from 4.46 to 5.91 lb/gal and normalized yield zone values range from 0 to 27. The drilling operation in this Zone/Formation is affected by reservoir in situ stresses.

The values of the normalized yield zone vs. the mud weight are displayed in Fig. 3. It is observed that with the increase of drilling mud weight from 4.6 to 5.8 lb/gal, the area of the normalized yield zone decreases from 27% to 0%. Figs. 5-6 depict the displacement modeling in X and Y directions. The maximum displacement in the X direction is 0.3621 mm, and in the Y direction is 0.8445 mm. The larger the displacements in the wellbore wall, the higher the tendency for wellbore instability, and vice versa.

Table 2. Normalized yield zone area vs. mud weight in Formation 1

Mud Weight (ppg)	Normalized Yielded Zone Area (%)
4.46	27
4.69	24
4.91	24
5.13	21
5.36	8
5.47	15
5.58	12
5.69	9
5.8	0
5.91	0

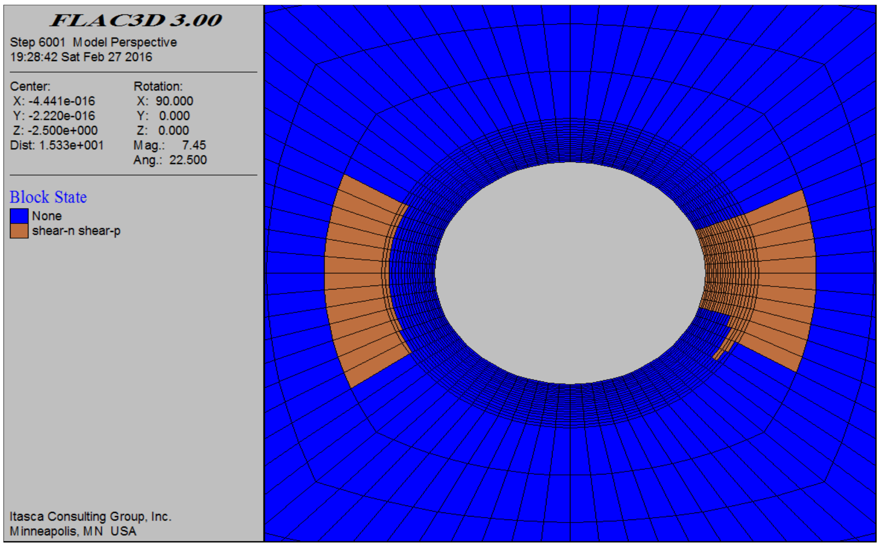

Fig. 2. Yield zone in Formation 1 using equivalent mud weight of 4.46 lb/gal

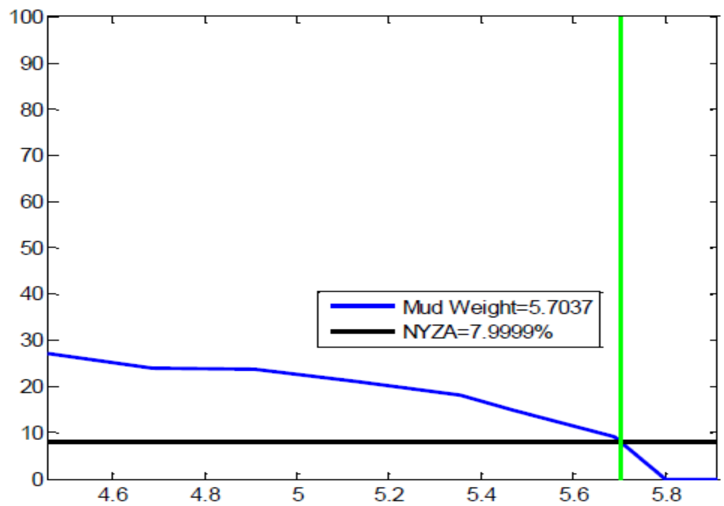

Fig. 3. Mud weight vs. normalized yield zone area in Formation 1

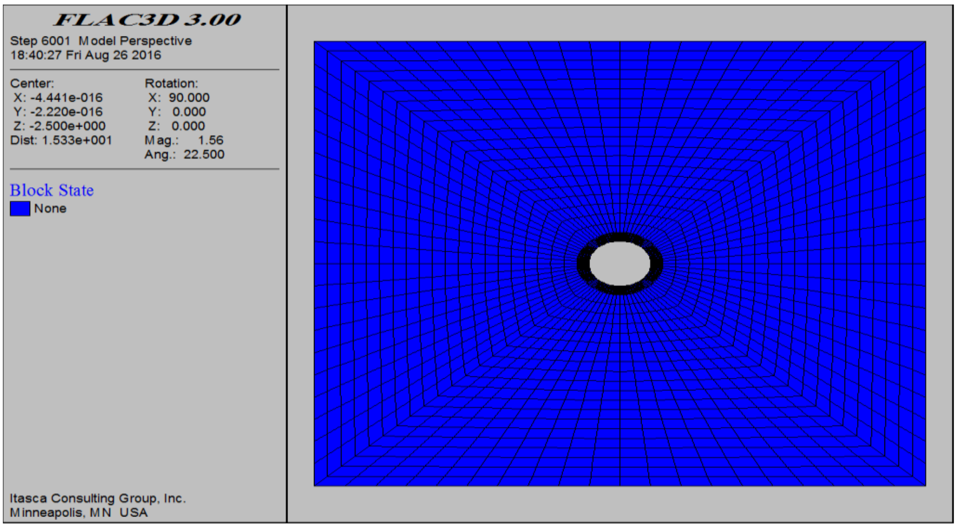

Fig. 4. Yield zone in Formation 1 using equivalent mud weight of 5.7 lb/gal

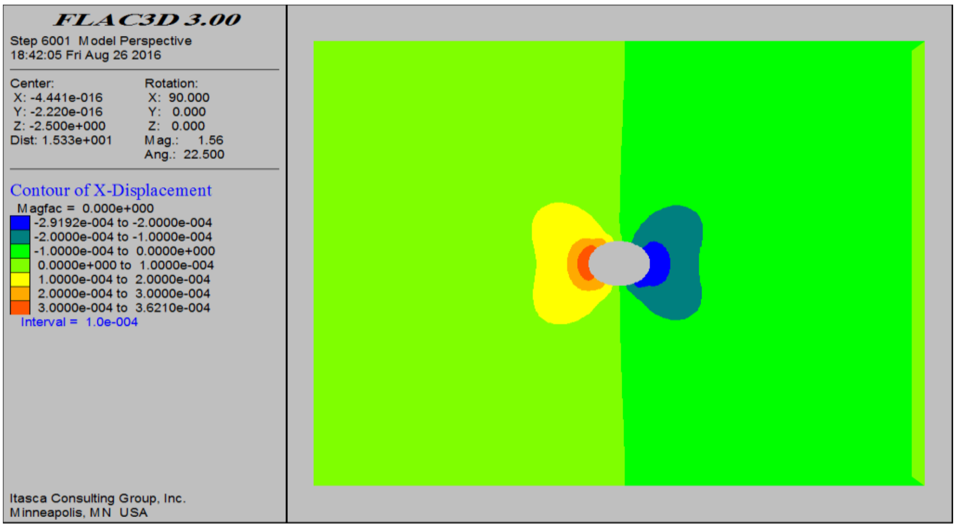

Fig. 5. Displacement in X direction in Zone 1 using equivalent mud weight of 5.7 lb/gal

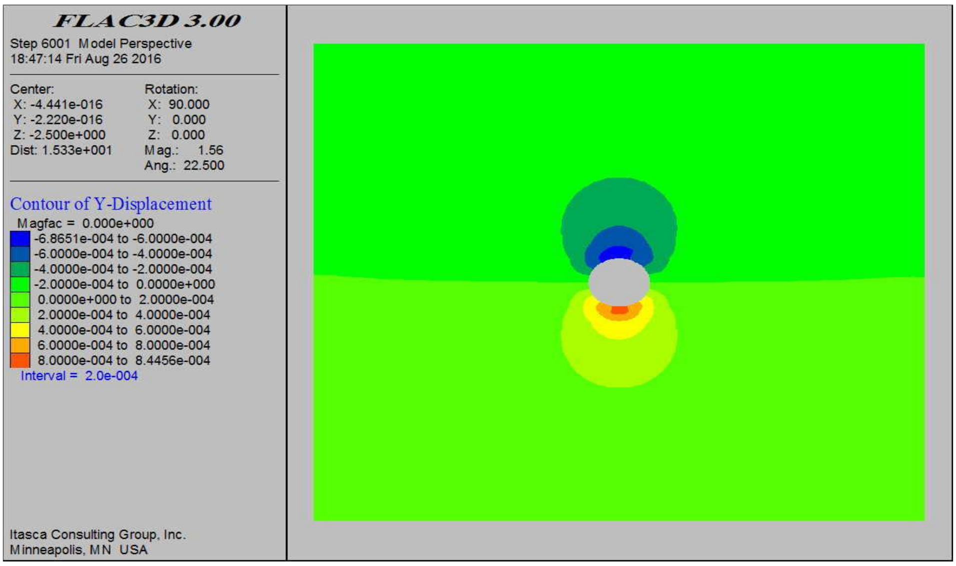

Fig. 6. Displacement in Y direction in Zone 1 using equivalent mud weight of 5.7 lb/gal

B. Wellbore Stability Modeling in Zone/Formation 2

Fig. 7 illustrates the yield zone in Formation 2 using a drilling mud with an equivalent weight of 4.95 lb/gal. Brown colors represent a non-safe drilling region in which the drilling operation has resulted in the collapse of the wellbore wall. Hence, the use of an appropriate mud weight to prevent the collapse of the wellbore wall is vital. Table 3 represents the normalized yield zone area vs. different mud weights. The mud weight is assumed to change between 4.95 to 7.54 lb/gal. The corresponding normalized yield zone area is in the range of 36% to 0%.

Assuming a normalized yield zone value equal to 8% in Fig. 8, the suitable mud weight for safe drilling is equal to 6.61 lb/gal, representing the appropriate mud weight for safe drilling without wellbore wall collapse. As observed, increasing mud weight has led to a decrease in the normalized yield zone area from 36% to 0%. In the next stage, the yield zone modeling was performed using an equivalent mud weight of 6.61 lb/gal, whose results are shown in Fig. 9. Figs. 10-11 depict the results for displacement modeling in X and Y directions. In this Zone, the maximum displacement in the X and Y directions is equal to 0.2448 mm and 0.6614 mm, respectively.

Table 3. Normalized yield zone area vs. mud weight in Formation 2

Mud Weight (ppg)	Normalized Yielded Zone Area (%)
4.95	36
5.17	31
5.38	30
6.03	21
6.46	12
6.68	5
6.8	0
7.11	0
7.32	0
7.54	0

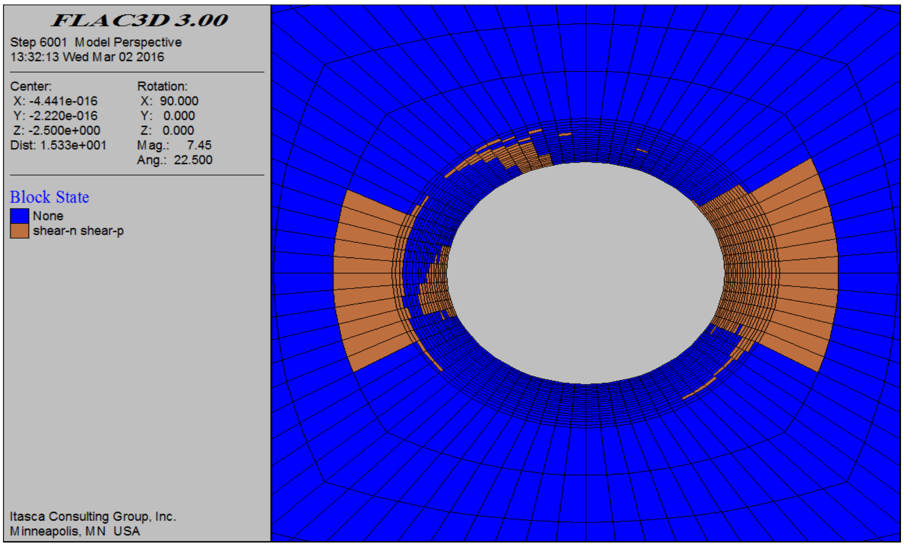

Fig. 7 Yield zone in Formation 2 using equivalent mud weight of 4.95 lb/gal

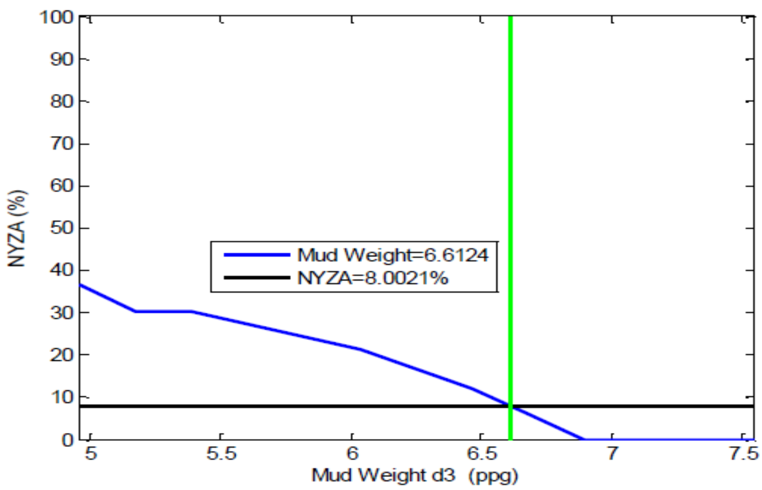

Fig. 8. Mud weight vs. normalized yield zone area in Formation 2

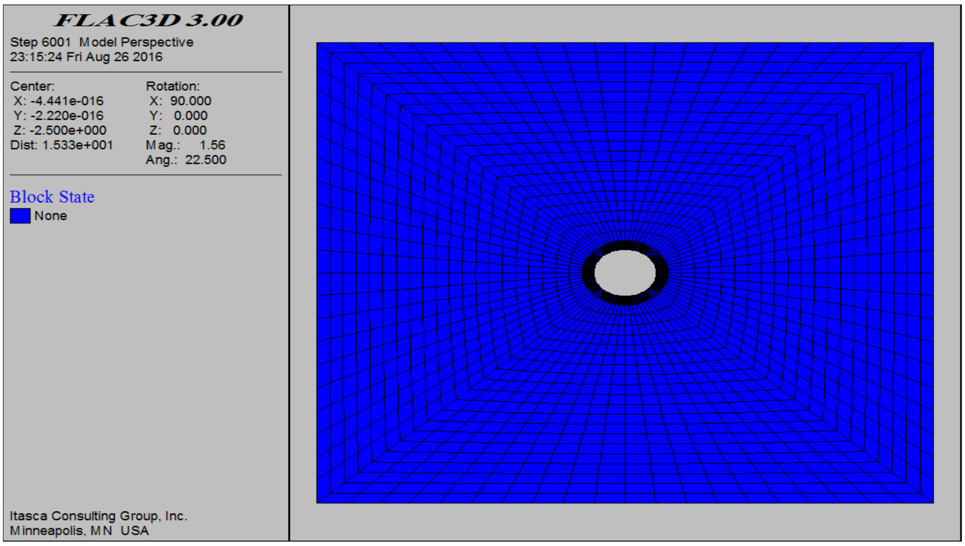

Fig. 9. Yield zone in Formation 2 using equivalent mud weight of 6.61 lb/gal

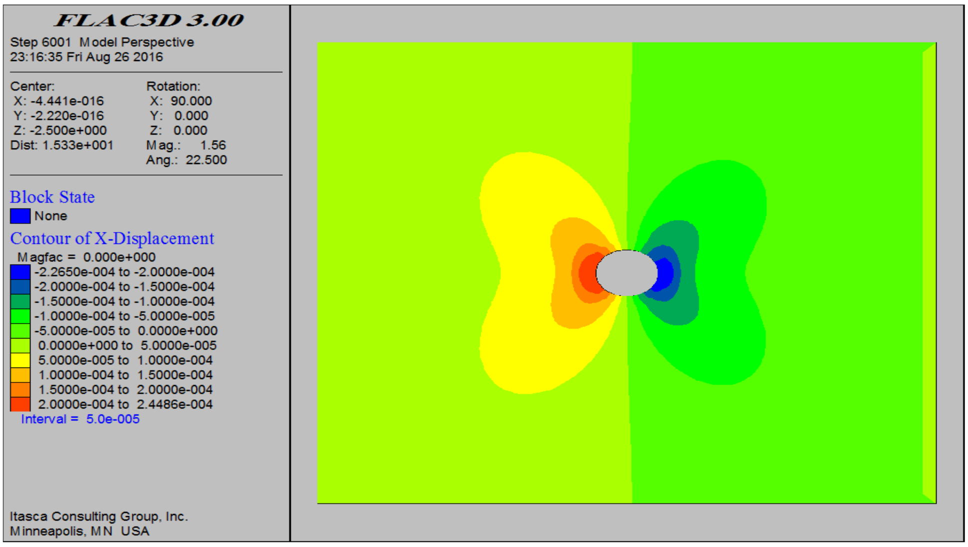

Fig. 10. Displacement in X direction in Zone 2 using equivalent mud weight of 6.61 lb/gal

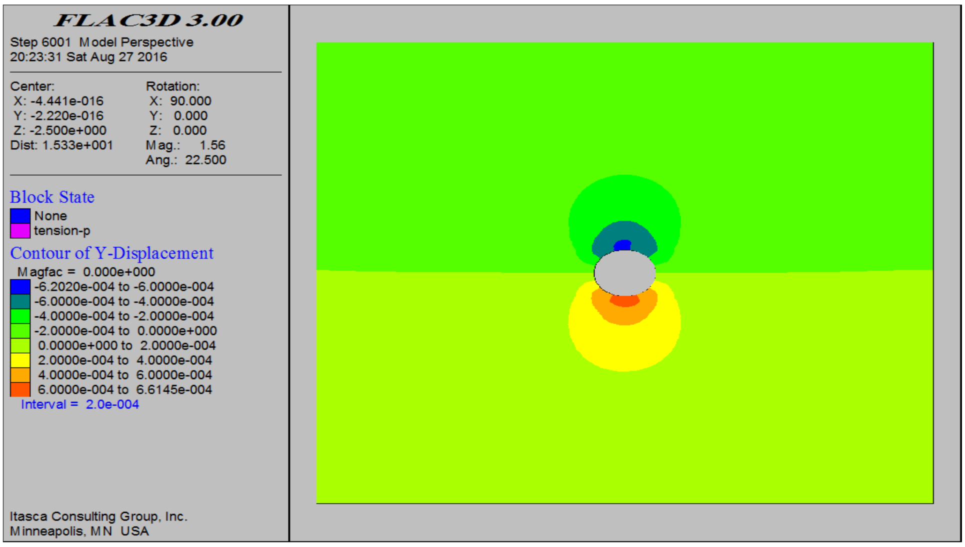

Fig. 11. Displacement in Y direction in Zone 2 using equivalent mud weight of 6.61 lb/gal

C. *Wellbore Stability Modeling in Zone/Formation 3*

Fig. 12 shows the yield zone in Formation 3 by using a drilling mud with an equivalent weight of 5.8 lb/gal. Points with a brown color indicate high stresses in the wellbore wall, which can result in the collapse of the wellbore wall while using a drilling mud with a 5.8 lb/gal weight. Table 4 represents the normalized yield zone area vs. different mud weights, in which the mud weight is assumed to change between 5.8 and 7.74 lb/gal. The corresponding normalized yield zone area is in the range of 40.4% to 0%.

Fig. 13 exhibits the mud weight vs. the normalized yield zone in Formation 3. The drilling operation using the equivalent mud weight of 7.43 lb/gal has given rise to safe drilling without wellbore wall collapse (Fig. 14). No unsafe drilling region can be seen in Fig. 14, demonstrating safe drilling using this equivalent mud weight. Figs. 15-16 depict the displacements in the X and Y directions in Zone 3, in which the maximum displacements in the X and Y directions are both equal to 0.059 mm.

Table 4. Normalized yield zone area vs. mud weight in Formation 3

Mud Weight (ppg)	Normalized Yielded Zone Area (%)
5.8	40.4
6.02	39.8
6.23	39.6
6.45	39.5
6.66	32.8
6.88	26.9
7.09	23.8
7.31	17.6
7.52	2.8
7.74	0

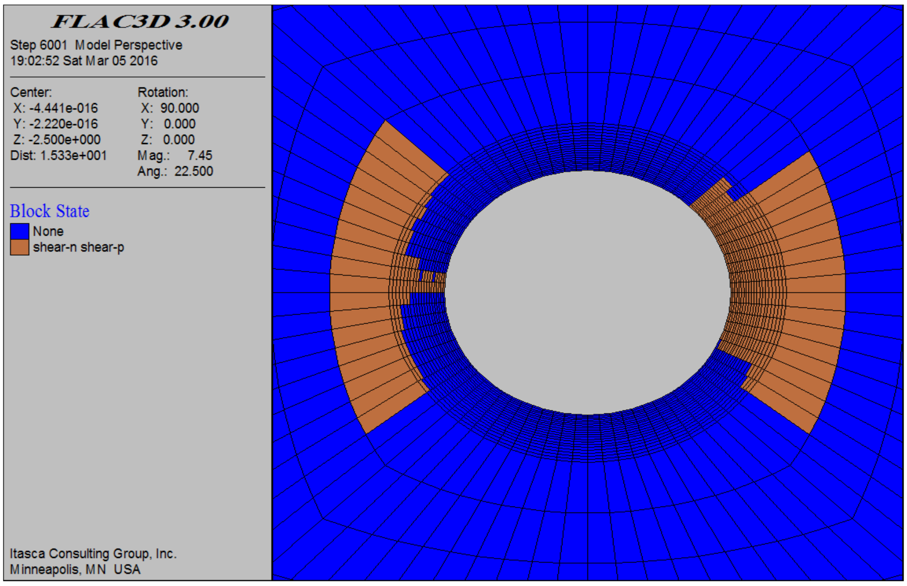

Fig. 12. Yield zone in Formation 3 using equivalent mud weight of 5.8 lb/gal

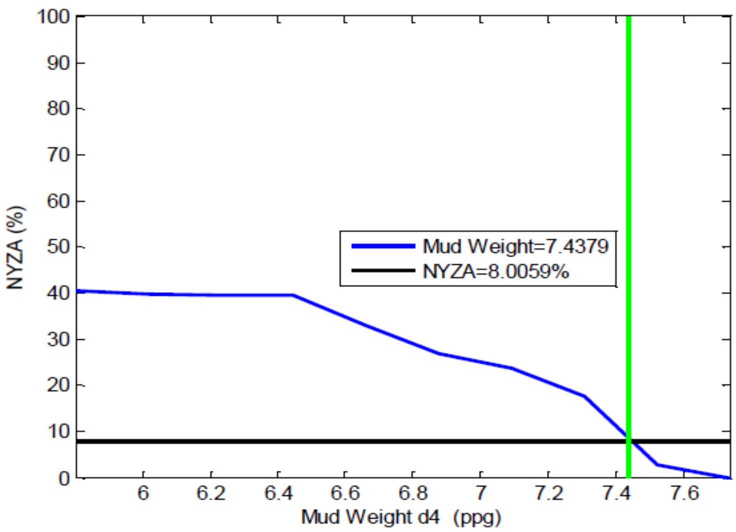

Fig. 13. Mud weight vs. normalized yield zone area in Formation 3

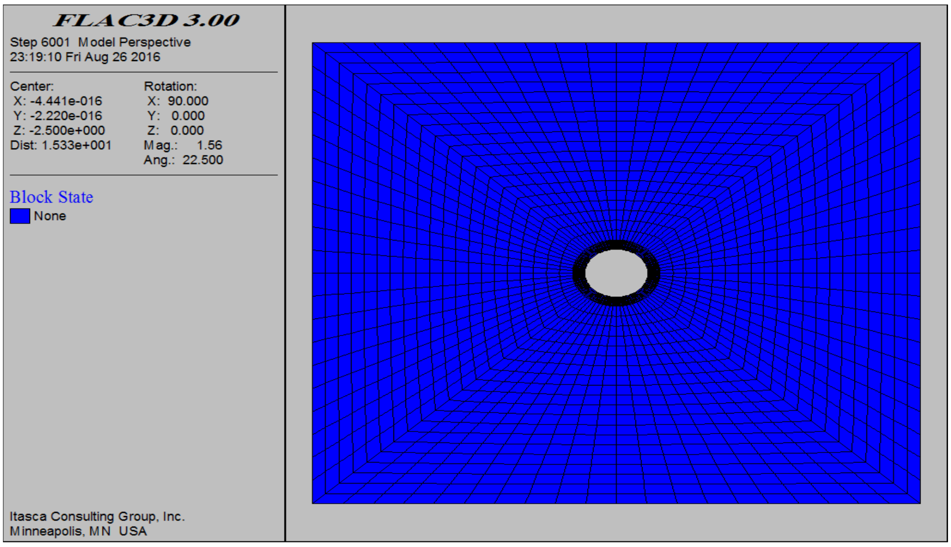

Fig. 14. Yield zone in Formation 3 using equivalent mud weight of 7.43 lb/gal

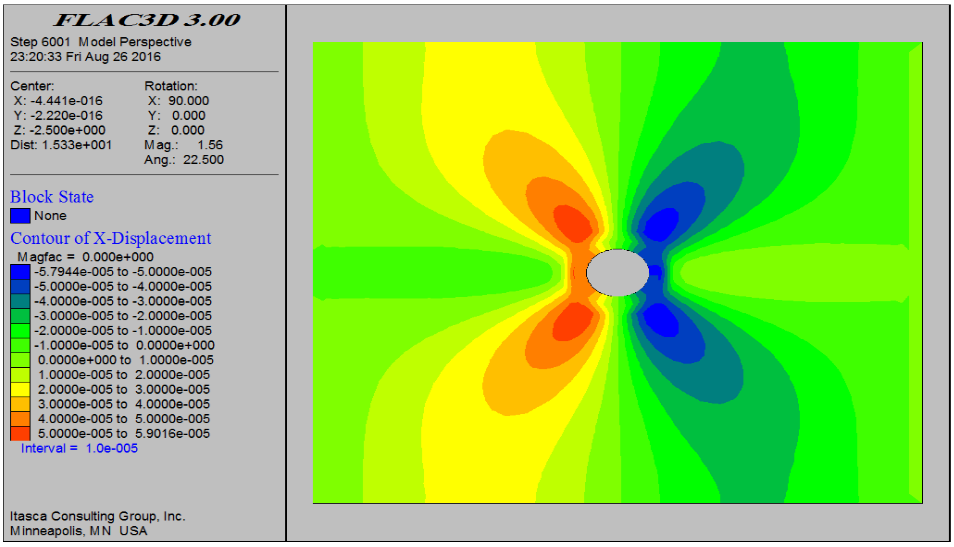

Fig. 15. Displacement in X direction in Zone 3 using equivalent mud weight of 7.43 lb/gal

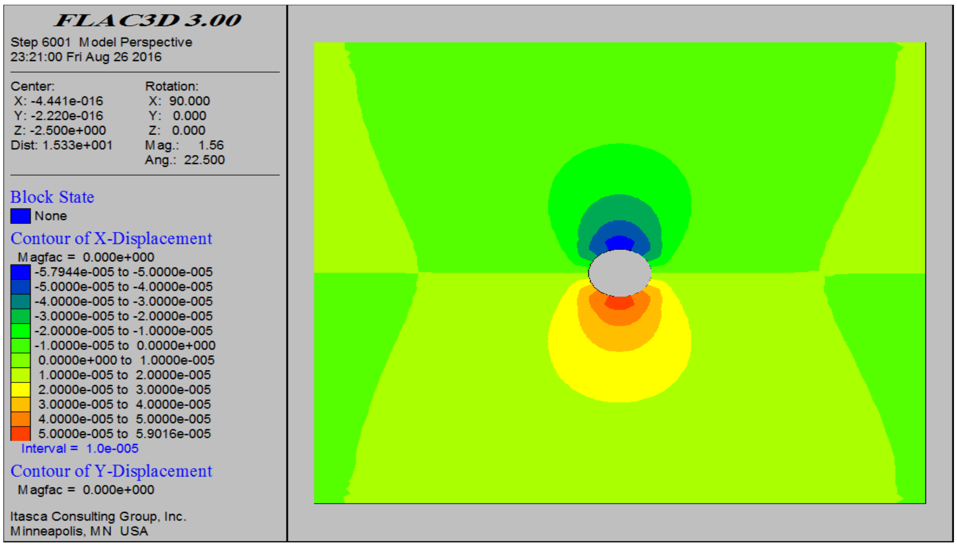

Fig. 16. Displacement in Y direction in Zone 3 using equivalent mud weight of 7.43 lb/gal

D. Wellbore Stability Modeling in Zone/Formation 4

Fig. 17 displays the yield zone in Formation 4 using a drilling mud with an equivalent weight of 5.01 lb/gal. Stresses existing on the wellbore wall shown by a brown color cause non-safe drilling in the wellbore, which in turn can result in wellbore wall collapse while using the drilling mud with a weight of 5.01 lb/gal. Table 5 presents the values of the normalized yield zone area for different

mud weights, in which the mud weight is assumed to change from 5.01 lb/gal to 6.89 lb/gal. The normalized yield zone area for this Formation ranges from 38.9% to 0%. Fig. 18 shows the mud weight vs. normalized yield zone area for Formation 4 .

Considering an 8% value for the normalized yield zone area, 6.51 lb/gal is obtained as the minimum suitable mud weight by which safe drilling without wellbore wall collapse is achieved (Fig. 19). Figs. 20-21 exhibit displacement results in the X and Y directions, with a maximum displacement of 0.0848 mm in both directions.

Table 5. Normalized yield zone area vs. mud weight in Formation 4

Mud Weight (ppg)	Normalized Yielded Zone Area (%)
5.01	38.9
5.22	35.1
5.43	43.3
5.63	31.2
5.84	25.9
6.05	22.6
6.26	22.4
6.47	10.8
6.68	0
6.89	0

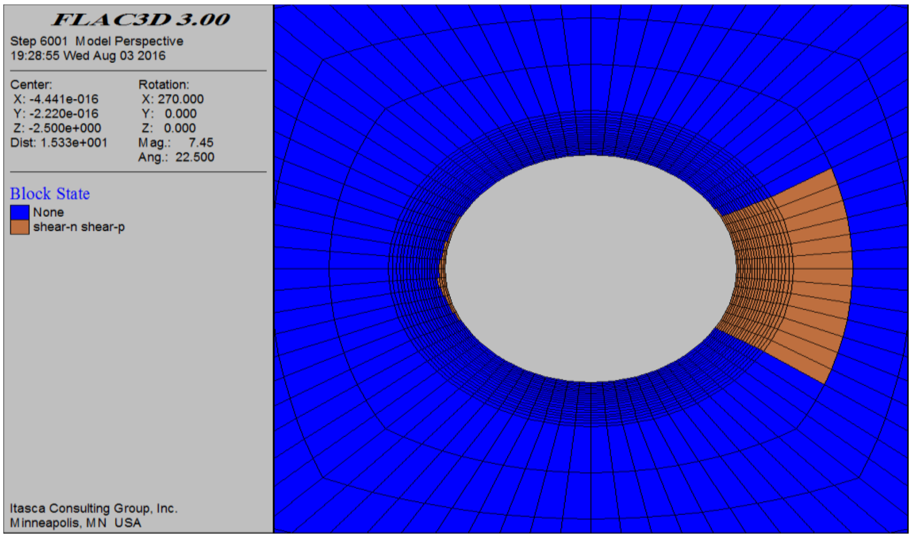

Fig. 17. Yield zone in Formation 4 using equivalent mud weight of 5.01 lb/gal

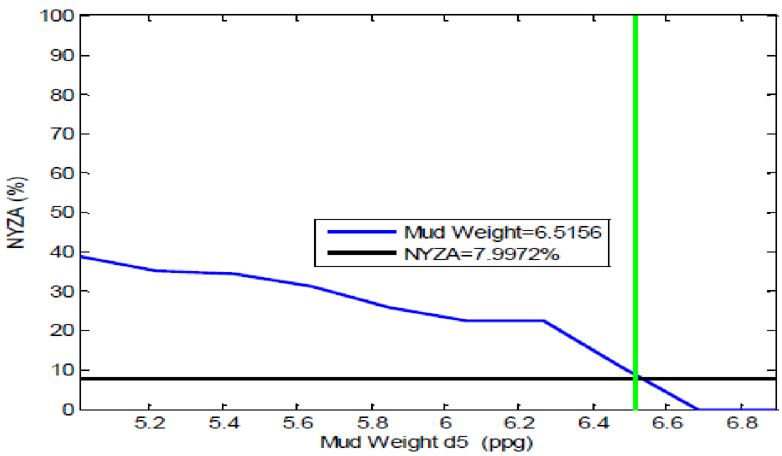

Fig. 18. Mud weight vs. normalized yield zone area in Formation 4

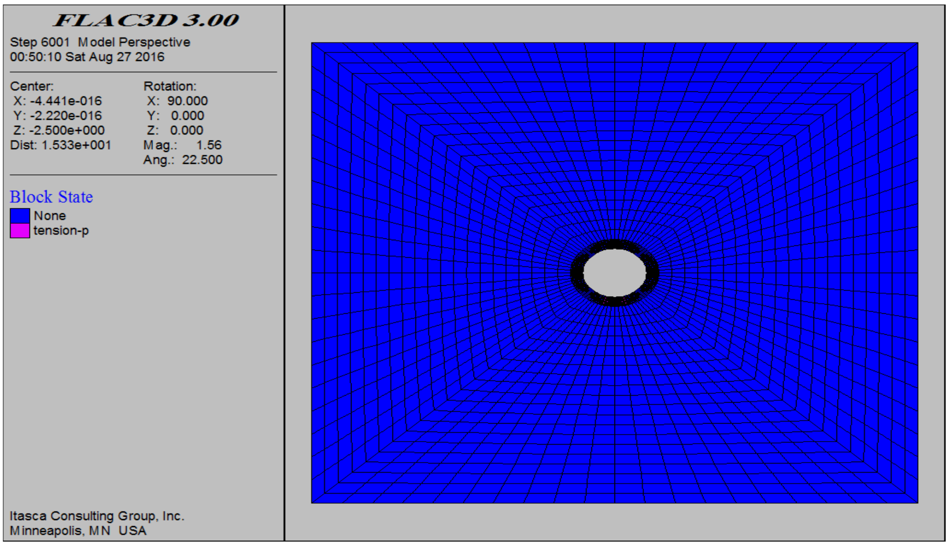

Fig. 19. Yield zone in Formation 4 using equivalent mud weight of 6.51 lb/gal

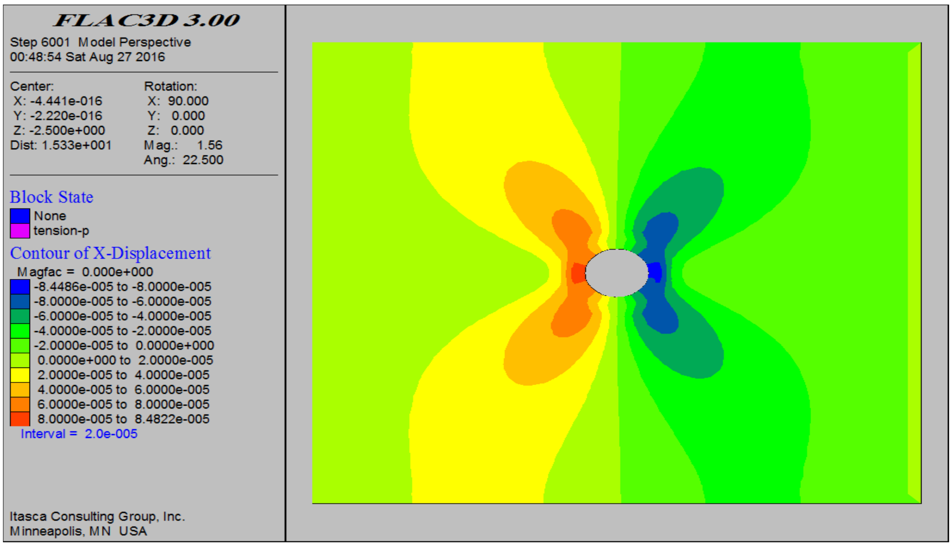

Fig. 20. Displacement in X direction in Zone 4 using equivalent mud weight of 6.51 lb/gal

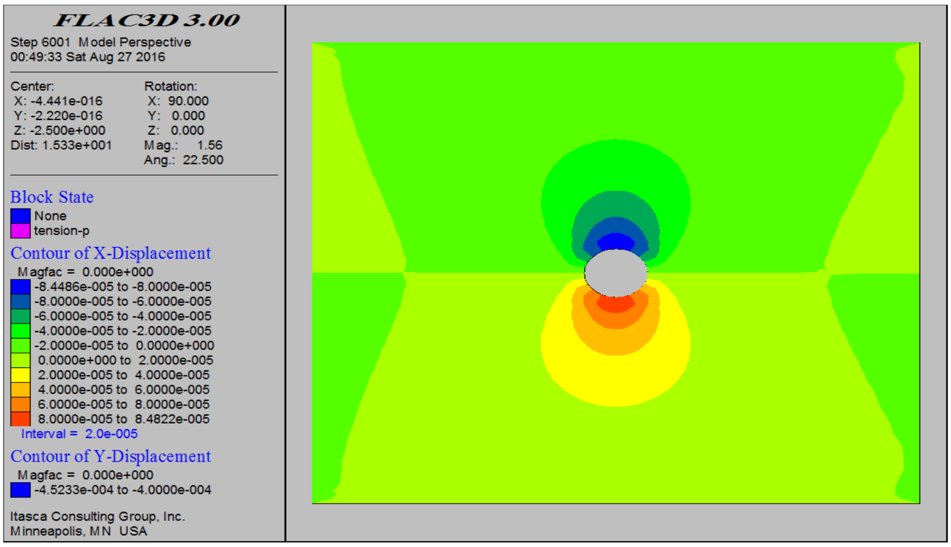

Fig. 21. Displacement in Y direction in Zone 4 using equivalent mud weight of 6.51 lb/gal

E. Wellbore Stability Modeling in Zone/Formation 5

Fig. 22 depicts the yield zone in Formation 5 using a drilling mud with an equivalent weight of 4.11 lb/gal. Brown colors represent the presence of excess stresses on the wellbore wall, which can lead to wellbore wall collapse while utilizing the drilling mud with a weight of 4.11 lb/gal. Table 6 presents a summary of the calculated values for the normalized yield zone area based on different mud weights. The drilling mud weight ranges from 4.11 lb/gal to 5.96 lb/gal in this Formation, causing a reduction in the normalized yield zone area from 23.6% to 0% .

Considering an 8% value for the normalized yield zone area, 5.05 lb/gal is obtained as the minimum suitable mud weight (Fig. 23), by which safe drilling without wellbore wall collapse is achieved (Fig. 24). Figs. 25-26 illustrate displacement results in the X and Y directions, with a maximum displacement of 0.291 mm in both directions. This reflects that the drilling operation is safe up to 0.291 mm in both directions, and beyond these displacements, further drilling gives rise to the collapse of the wellbore wall. Table 7 presents the minimum mud weight for safe drilling in different formations. The highest minimum mud weight (7.43 lb/gal) belongs to Formation 3. Fig. 27 displays the changes in drilling mud pressure (using the minimum mud weight of 7.43 lb/gal) and pore pressure vs. depth. As observed, pore pressure in the target depths is always greater than drilling mud pressure, indicating that the drilling operation is under-balanced in this oil field. Considering 7.43 lb/gal as the optimum mud weight in all formations, the drilling operation can be carried out safely without wellbore wall collapse.

Table 6. Normalized yield zone area vs. mud weight in Formation 5

Mud Weight (ppg)	Normalized Yielded Zone Area (%)
4.11	23.6
4.32	20.4
4.52	19.6
4.73	14.4
4.96	14
5.14	3
5.35	1.5
5.55	0
5.76	0
5.96	0

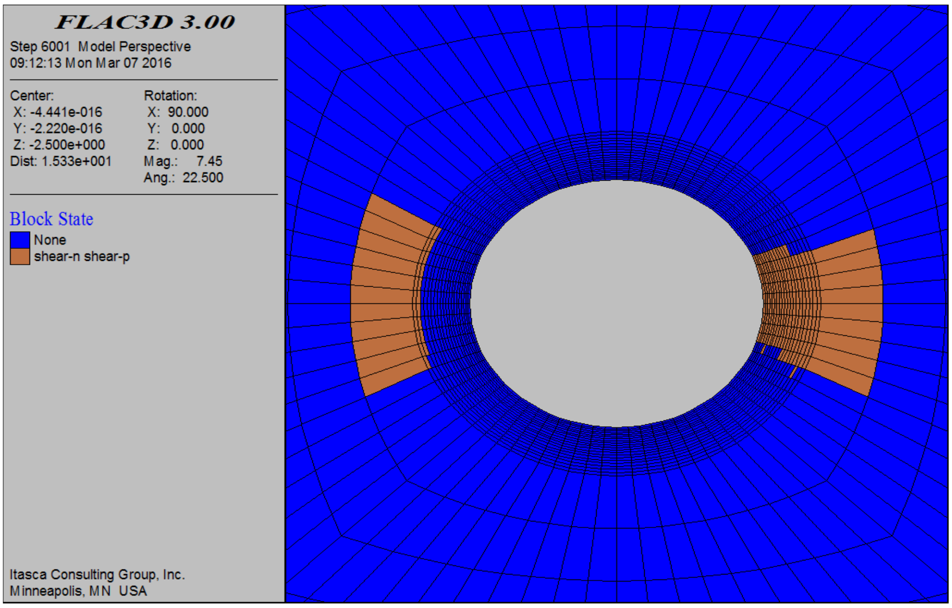

Fig. 22. Yield zone in Formation 5 using equivalent mud weight of 4.11 lb/gal

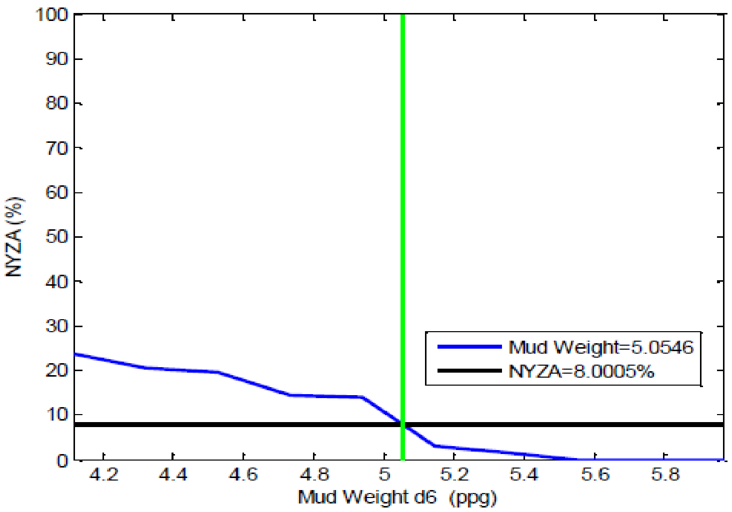

Fig. 23. Mud weight vs. normalized yield zone area in Formation 5

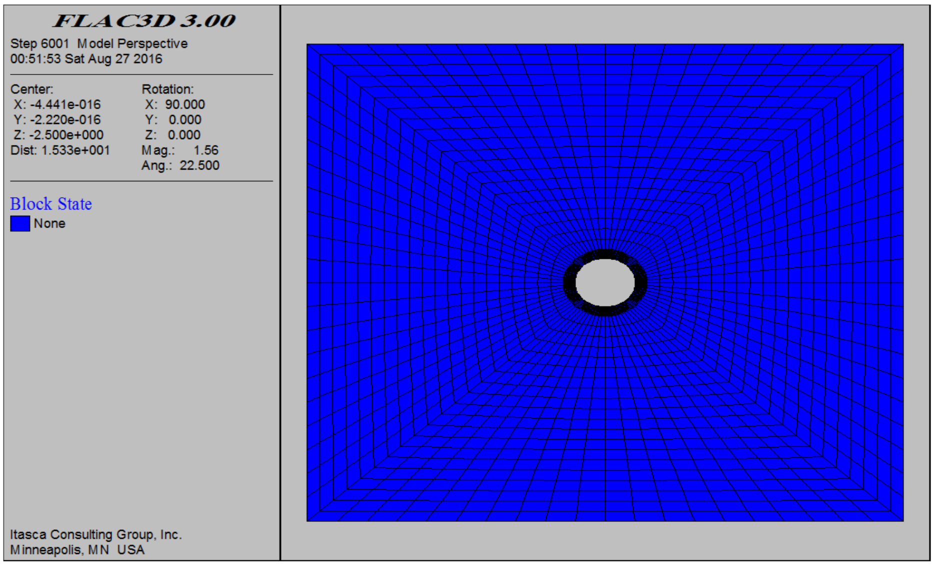

Fig. 24. Yield zone in Formation 5 using equivalent mud weight of 5.05 lb/gal

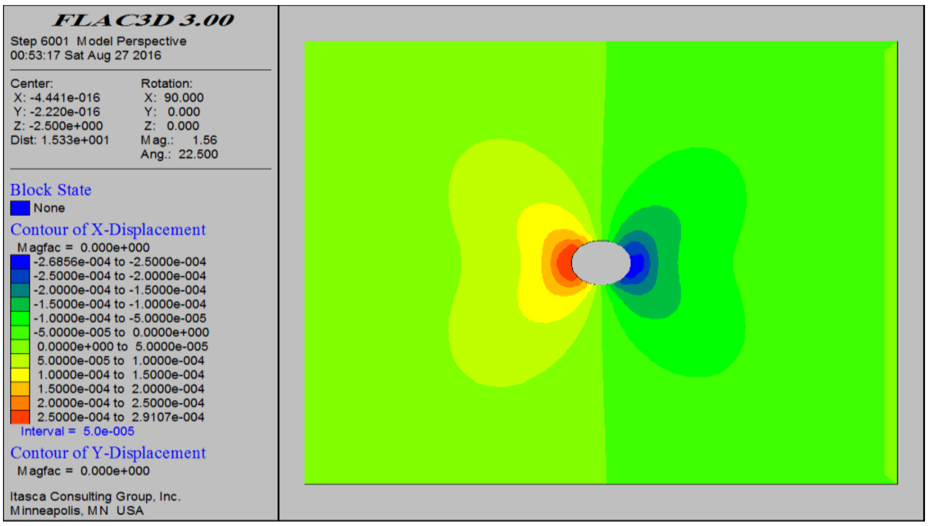

Fig. 25. Displacement in X direction in Zone 5 using equivalent mud weight of 5.05 lb/gal

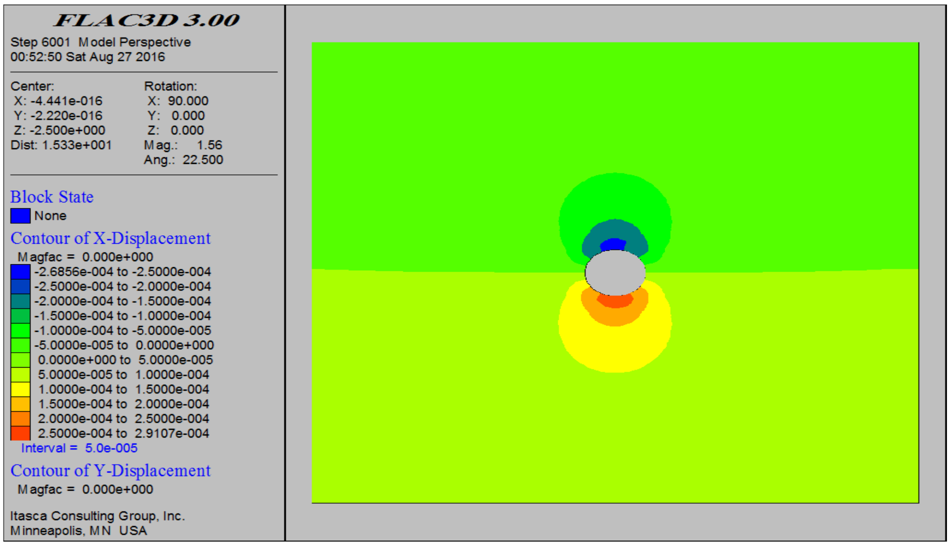

Fig. 26. Displacement in Y direction in Zone 5 using equivalent mud weight of 5.05 lb/gal

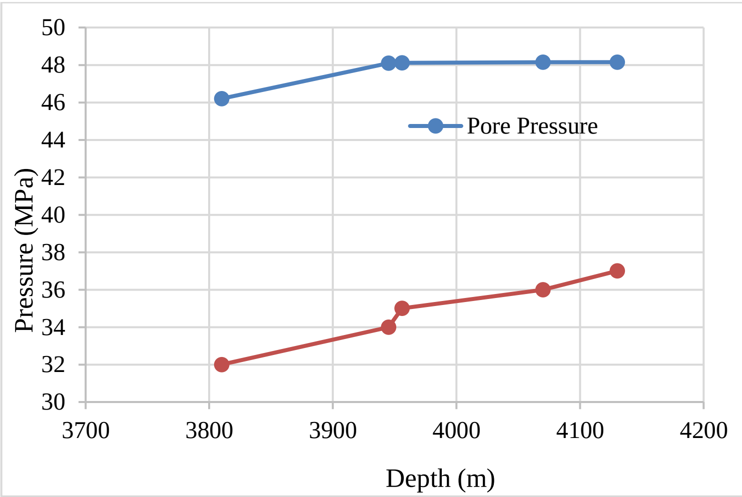

Fig. 27. Changes of drilling mud pressure (using the minimum mud weight of 7.43 lb/gal) and pore pressure vs. depth

Table 7. The minimum mud weight in different formations

Formation	Minimum mud weight (ppg)	Maximum displacement in X direction (mm)	Maximum displacement in Y direction (mm)
1	5.7	0.3621	0.8445
2	6.61	0.2448	0.6614
3	7.43	0.059	0.059
4	6.51	0.0848	0.0848
5	5.05	0.291	0.291

VI. CONCLUSION

Flac3D was employed to determine wellbore wall stability. For this purpose, five different formations of the target oil field were evaluated, and the role of mud weight on the stability of the wellbore wall was investigated. The main research results are as follows:

1) The following results were acquired for Formations 1-5, respectively:

a) The minimum mud weight (lb/gal): 5.7, 6.61, 7.43, 6.51, 5.05

b) The maximum displacement in the X direction (mm): 0.3621, 0.2448, 0.059, 0.0848, 0.291

c) The maximum displacement in the Y direction (mm): 0.8445, 0.6614, 0.059, 0.0848, 0.291

2) The minimum mud pressure for this oil field leading to safe drilling in all formations without wellbore wall collapse was considered for the mud weight of 7.43 lb/gal. The diagram of the changes in drilling mud pressure (using the aforementioned mud weight) and pore pressure vs. depth demonstrated that pore pressure is always greater than drilling mud pressure, suggesting that the drilling operation is under-balanced in this oil field.

Flac3D is a finite difference-based software that provides solutions only on nodes of the defined finite difference network. This means that it cannot provide information for spaces between the defined nodes. Using finite element-based software such as ABAQUS is recommended for future studies, not only to address this deficiency but also to be used for comparison with the results obtained in this study and so as a means for validating our research outcomes.

REFERENCES

Fang, C., Wang, Q., Jiang, H., Chen, Z., Wang, Y., Zhai, W., Chen, S. (2023). Shale wellbore stability and well trajectory optimization: a case study from Changning, Sichuan, China. Petroleum Science and Technology. 4, 41(5), 564-85.

Guerrero, E., Pinilla, A., Ratkovich, N. (2020). Assessment of well trajectory effect on slug flow parameters using CFD tools. Chemical Engineering Communications. 2, 207(10), 1390-402.

Wang, W., Schmitt, D.R., Li, W. (2022). A program to forward model the failure pattern around the wellbore in elastic and strength anisotropic rock formations. International Journal of Rock Mechanics and Mining Sciences.1, 151, 105035.

Yang, X., Shi, X., Meng, Y., Xie, X. (2022) Wellbore stability analysis of layered shale based on the modified Mogi–Coulomb criterion. Petroleum.1, 6(3), 246-52.

Tran, N.H., Do, D.P., Vu, M.N., Nguyen, T.T., Pham, D.T., Trieu, H.T. (2022). Combined effect of anisotropy and uncertainty on the safe mud pressure window of horizontal wellbore drilled in anisotropic saturated rock. International Journal of Rock Mechanics and Mining Sciences. 1, 152, 105061.

Kanfar, M.F., Chen, Z., Rahman, S.S. (2015). Effect of material anisotropy on time-dependent wellbore stability. International Journal of Rock Mechanics and Mining Sciences. 1, 78, 36-45.

Kim, S., Yun, Y., Choi, J., Bizhani, M., Kim, T.W., Jeong, H. (2022). Prediction of maximum slug length considering impact of well trajectories in British Columbia shale gas fields using machine learning. Journal of Natural Gas Science and Engineering. 1, 106, 104725.

Wang, N., Cheng, Z., Lu, Y., Jiang, W., Zhou, J., He, B., Ren, G. (2015). A multibody dynamics model of contact between the drillstring and the wellbore and the rock penetration process. Advances in Mechanical Engineering. 6, 7(5), 1687814015582117.

Al-Qahtani, M.Y., Zillur, R. (2001). A mathematical algorithm for modeling geomechanical rock properties of the Khuff and Pre-Khuff reservoirs in Ghawar field. InSPE Middle East Oil and Gas Show and Conference, 2001 Mar 17 (pp. SPE-68194). SPE.

Mohiuddin, M.A., Awal, M.R., Abdulraheem, A., Khan, K. (2001). A new diagnostic approach to identify the causes of borehole instability problems in an offshore Arabian field. InSPE Middle East Oil and Gas Show and Conference, 2001 Mar 17 (pp. SPE-68095). SPE.

Al-Ruwaili, S.B., Chardac, O. (2003). 3D model for rock strength & in-situ stresses in the Khuff formation of Ghawar field, methodologies & applications. InSPE Middle East Oil and Gas Show and Conference, 2003 Jun 9 (pp. SPE-81476). SPE.

Ahmed, M.S., Finkbeiner, T., Kannan, A.A. (2007). Using geomechanics to optimize field development strategy of deep gas reservoir in Saudi Arabia. InSPE Asia Pacific Oil and Gas Conference and Exhibition, 2007 Oct 30 (pp. SPE-108891). SPE.

Al-Wardy, W., Urdaneta, O.P. (2010). Geomechanical modeling for wellbore stability during drilling Nahr Umr shales in a field in petroleum development Oman. InAbu Dhabi International Petroleum Exhibition and Conference, 2010 Nov 1 (pp. SPE-138214). SPE.

Abalioglu, I., Legarre, H., Garland, C., Sallier, B., Gao, J., van Galen, M., Chou, Q., Neil, B., Soroush, H., Qutob, H., Mahli, Z. (2011). The role of geomechanics in diagnosing drilling hazards and providing solutions to the northern Iraq fields. InSPE Middle East Oil and Gas Show and Conference 2011 Sep 25 (pp. SPE-142022). SPE.

Qiuguo, L., Zhang, X., Al-Ghammari, K., Mohsin, L., Jiroudi, F., Al-Rawahi, A. (2013) 3D geomechanical modeling, wellbore stability analysis improve field's performance. World Oil journal published by Gulf Publishing Company, 53-61.

Mohammed, H.Q., Abbas, A.K., Dahm, H.H. (2018). Wellbore instability analysis for Nahr Umr Formation in southern Iraq. InARMA US Rock Mechanics/Geomechanics Symposium, 2018 Jun 17 (pp. ARMA-2018). ARMA.

Bagheri, H., Tanha, A.A., Doulati Ardejani, F., Heydari-Tajareh, M., Larki, E. (2021). Geomechanical model and wellbore stability analysis utilizing acoustic impedance and reflection coefficient in a carbonate reservoir. Journal of Petroleum Exploration and Production Technology, 11, 3935-61.

Hoseinpour, M., Riahi, M.A. (2022). Determination of the mud weight window, optimum drilling trajectory, and wellbore stability using geomechanical parameters in one of the Iranian hydrocarbon reservoirs. Journal of Petroleum Exploration and Production Technology. 1, 1-20.

Al-Shuwaili, J.M.Y. (2024) Application of One-dimensional Geo-mechanical Modeling and Determination of Optimal Rock Fracture Criteria in the Design of Wellbore Safe Path in the Southern Iraq Oil Fields. M.Sc. thesis, Islamic Azad University (Science and Research Branch), Tehran.