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Geomechanical modeling and wellbore stability analysis for studying the shale rock failure

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Abstract

Wellbore stability constitutes a critical challenge that can precipitate an escalation in non-productive time (NPT) during drilling operations, subsequently resulting in an increase in well expenditures and consequent revenue deficits. Shale formations exhibit a greater propensity than many geological formations to induce complications during the drilling process. Consequently, advanced geomechanical analyses were executed on select wells within the Zubair oilfield to clarify the fundamental causes of instability predominant in the field. In this study, the model was applied to two specific wells (ZB-A and ZB-B) to perform a wellbore stability assessment utilizing available well log data, which includes parameters such as bit size (BS), caliber (CAL), shear sonic logs (DTS), compressional sonic logs (DTC), and gamma ray (GR) logs. Laboratory-derived data in addition to the minimum horizontal stress that were refined using the leak-off test (LOT) measurements. The predicted formation pore pressures were calibrated against the pore pressure readings obtained from a repeated formation tester (RFT). The Mogi-Coulomb failure criteria were employed to ascertain the safe operating mud window requisite for balanced drilling, owing to the criterion's capacity to accommodate the intermediate principal stress (σ2). The proposed mud weight values, derived from the model, range from 1.32 g/cc to 1.45 g/cc, whereas a mud weight of 1.19 g/cc was utilized during the drilling operations. The findings of this research can be used as a guide to choose the best mud weight to solve problems related to wellbore instabilities in this field.

Keywords: *Wellbore stability; geomechanical analysis; shale rock failure; Mogi-Coulomb failure criterion; mud weight optimization.*

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1- Introduction

Wellbore stability difficulties are one of the main reasons that increase the NPT through drilling operations [1, 2]. Well instability can take many forms, including a reduction in hole size caused by the rock being squeezed into the inside of the hole, borehole stress induced enlargement (breakouts) caused by shale formations or hard rock spalling, pipe sticking, and loss circulation caused by high wellbore drilling fluid pressure or rock breakdown failure. To keep the wellbore stable, it is good practice to understand the factors that influence the borehole, thus, the wellbore failure can be predicted and applied through the rock mechanics concepts [3]. A mechanical earth model (MEM) is a collection of data measurements and models that show the mechanical characteristics of the rocks as well as fractures, stresses, pressures and temperatures that act on rock at each depth. It is used to understand how rocks deform or fail as a response to the drilling operations, completion and production strategies [4, 5]. To achieve that, it is important to construct a geomechanical model that can consider the mechanical and elastic properties of formation as well as both pore pressures and in-situ stresses. By using this model, failure criteria can be used to predict the minimum and maximum limits of mud weights needed to pass the formation with less expected drilling problems or with less rock failure. Thus, it is important to select the correct failure criterion that can reflect the far-field stresses and the stresses around the wellbore.

The Mohr-Coulomb criterion is the most widely used failure criterion, however, it tends to assume that the intermediate principal stress (σ_2) does not affect the strength of the rock. A few studies have found problems with the application of this criterion. Vernik discovered that the Mohr-Coulomb criterion could not be used to determine the borehole breakout dimensions [6]. This failure criterion has two massive flaws: (a) it does not consider that strength does not behave in a straight line, and (b) it does not consider the influence of intermediate principal stress in its normal form. So, many failure criteria have been made to consider the influence of the intermediate principal stress on how rocks behave when they are subjected to stress. But most of these criteria are mathematically limited and lead to solutions that do not make sense in real field conditions. The Mogi–Coulomb criterion overlooks the impact of intermediate principal stress and predicts results that are good and realistic.

Al-Kattan, Wafa conducted research to produce ways that can figure out some mechanical characteristics from conventional logs such as sonic, density and gamma ray

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for a well in the North Rumaila field. Formation strength and Poisson's ratio were two examples of the mechanical properties that were extracted [7]. Hadi et al. introduced the probability theory for determining the uncertainty behind the geomechanical properties that may affect the prediction of mud weight. Accordingly, the maximum horizontal stress has a significant influence on determining the state of failure, i.e., on selecting the efficient mud weights to keep the wellbore stable. Other properties, including internal friction angle, rock cohesion, vertical stress, minimum horizontal stress and pore pressure, have a decreasing influence on determining the rock failure [8]. Al-Zubaidi and Al-Neeamy presented a three-dimensional mechanical earth model (3D MEM) for an oilfield in southern Iraq. They stated that the 3D MEM has several advantages through the field life; it can determine the optimal direction of the directional wells, whereas the one-dimensional mechanical earth model (1D MEM) can reduce the instability problems. The results of their work showed a tight mud window in the frontal part of the Tanuma formation [9]. Al-Shibli, Fadhil had performed an experimental work in the lab to figure out how shale and drilling mud are chemically reacted. Chemical connections must be kept to a minimum by using the appropriate drilling mud with the proper chemicals added. This study was conducted because of the problems that keep coming up when drilling through the Tanuma formation, which is known as one of the hardest operations due to the instability problem [10]. Junliang Yuan demonstrated the fact that borehole instability is not only dependent on the inclination and azimuth of the well, but it also relies on the placement of the bedding planes that make up the formation. From the perspective of borehole stability, a direction that is normal to the bedding planes is the most preferable trajectory for a borehole to undertake. If the bedding orientation is perpendicular to the trajectory of S_h in a horizontal well, the possibility of instability is quite substantial for most drilling directions besides drilling along the dip orientation of the bedding planes [11].

In this study, a 1D-MEM was conducted via analyzing several types of available data to figure out the wellbore stability issues in the Zubair oilfield. Two selected wells from this field were chosen to conduct this study where drilling and geological reports showed some NPT related to wellbore stability issues.

2- Field under study

Zubair oilfield was discovered by Basrah Petroleum Company (BPC) in 1948. It is located 20 km to the west of Basrah, in southern Iraq. Nahr Umr oilfield is located to the north of Zubair oilfield, while Rumaila oilfield is to the west, as shown in Fig. 1. Zubair oilfield is an anticlinal structure 61 km long and 8 km wide that has a flank with a 2-3° dip and NNW-SSE strike. It has two culminations: the northern, the Hammar Dome, and the southern, the Rafidya Dome Fig. 2.

The hydrocarbons can be found in the Lower Fars formation as well as the Mishrif and Zubair formations. The two sand members in the Zubair formation are considered the main producers; the upper member produces oil with 36° API, while the lower member has oil with 42° API [12].

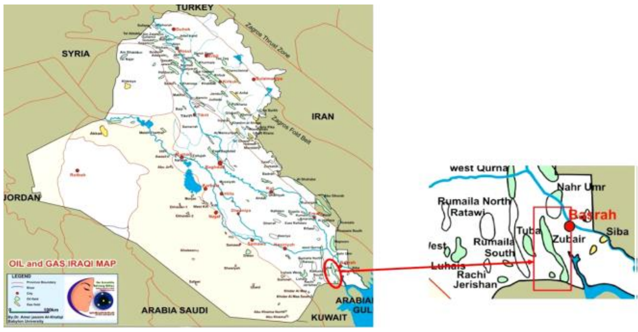


Fig. 1. Zubair Oilfield Map, [12]

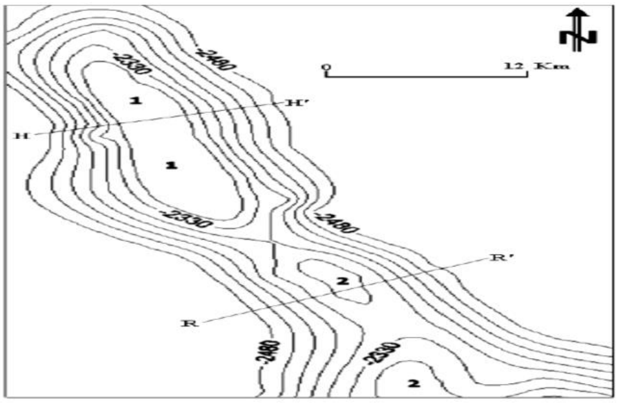


Fig. 2. Structural map of Zubair oilfield [12]

3- Geomechanical Modeling

A one-dimensional mechanical earth model will be created using Techlog 2015 software, and raw data from the field will be examined to guarantee the model's accuracy. The essential steps for constructing a one-dimensional earth model are presented as a flow chart in Fig. 3.

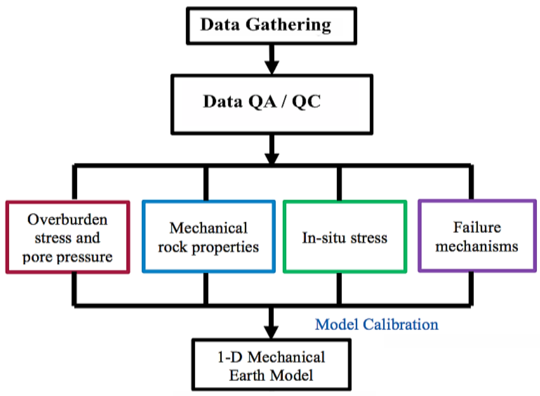


Fig. 3. 1D MEM workflow steps

3.1. Vertical stress calculation

It is also known as overburden stress, which is the pressure exerted on the rock at any depth due to the weight of the rocks combined with fluid of the pores which lies on the top of the selected rock. The average formation bulk and pore pressure gradient may be used to calculate the overburden stress [4].

$$\sigma v = \int_0^z \rho g\,(z) dz \quad (1)$$

Where: σv: overburden pressure (psi). ρ: Rocks' overall density. G: Acceleration by gravity (m/s²). Z: formation depth (m).

3.2. Pore pressure calculation

The original Eaton slowness approach method is one of the most used methods for determining pore pressure from acoustic log data. This approach was developed in 1975 to calculate pore pressure, initially using log resistivity data and then improving the equation to determine pore pressure count using sonic log data [13].

$$Pp = \sigma v - (\sigma v - Ppn) * a * \left(\frac{\Delta tnorm}{\Delta t}\right)^n \quad (2)$$

Where: Δt_{norm}: This is the normal slowness in shale formations. Δt is the slowness from the sonic log in the shale formation. "a" and "n" are fitting factors; Eaton factor and Eaton exponent, respectively. The default values are a = 1 and n=3. Ppn: is the hydrostatic pore pressure.

3.3. Rock mechanical properties

For a detailed evaluation of the instability of the wellbore, estimation of stress and prediction of mud weight. It is important to know the elastic strength and tensile strength specifications of the rock. Most of the time, the static and dynamic methods are used to figure out the mechanical properties of rocks. If you cannot get the rock's static measurements, the dynamic parameter should be changed to its static form. The mechanical properties of the rock measured in the lab have also been added to the plot so that the degree of agreement between the experimental measurements done on the rock and the logs made can be calibrated.

a. Rock strength properties

Rock strength variables, including unconfined compressive strength (UCS), cohesive strength (C), and internal angle of fraction (φ), show how well the rocks can manage the stresses around the wellbore. Most of the time, the UCS and friction angle are used to measure the strength of rocks in geomechanical modeling. In this study, Eq. 3 and Eq. 4 were used to calculate the internal friction angle for shale and sandstone formations, respectively, and Eq. 5 was used to calculate the UCS [14].

$$\varphi = tan^{-1}\left(\frac{78-0.4GR}{60}\right) \quad (3)$$

$$\varphi = 57.8 - 105\, GR \quad (4)$$

$$UCS = 331 + 0.0041\, Esta \quad (5)$$

Where: Φ: Internal friction angle. GR: Gamma ray log readings. UCS: Unconfined compressive strength. E_{sta}: Static Young modulus.

b. Tensile strength (T_o)

This is one of the important parameters for calculating rock resistance and horizontal stress magnitudes. The rocks appear to have very low tensile strength; therefore, the rock fracture normally appears to be brittle (breaks quickly), and there is no plastic deformation after reaching tensile strength [15]. In this work, Eq. 6 is used to calculate the tensile strength.

$$To = UCS * K \quad (6)$$

Where k= Facies and zone-based factor

c. Elastic properties

Figuring out the modulus of elasticity is to find out how the rock behaves or deforms when it’s subjected to the applied stresses. The elastic mechanical properties of the rock include Young's modulus, Poisson's ratio, the shear modulus and the bulk modulus. The elastic mechanical properties can be estimated by performing numerous static rock tests or by analyzing well log data such as density and sonic log data. The shear and compression slowness of the sonic log are examples of dynamic measurements. Usually, dynamic measurement is greater than static measurement. In the present paper, the dynamic elastic properties were calculated from equations 7, 8, 9, and 10, respectively [14].

$$Ed = \frac{9Gd*kd}{Gd+3Kd} \quad (7)$$

$$Gd = 13474.45 \frac{Pb}{\Delta ts^2} \quad (8)$$

$$Kd = 13474.45\, \rho b \left(\frac{1}{\Delta tc^2} - \frac{4}{3\Delta ts^2}\right) \quad (9)$$

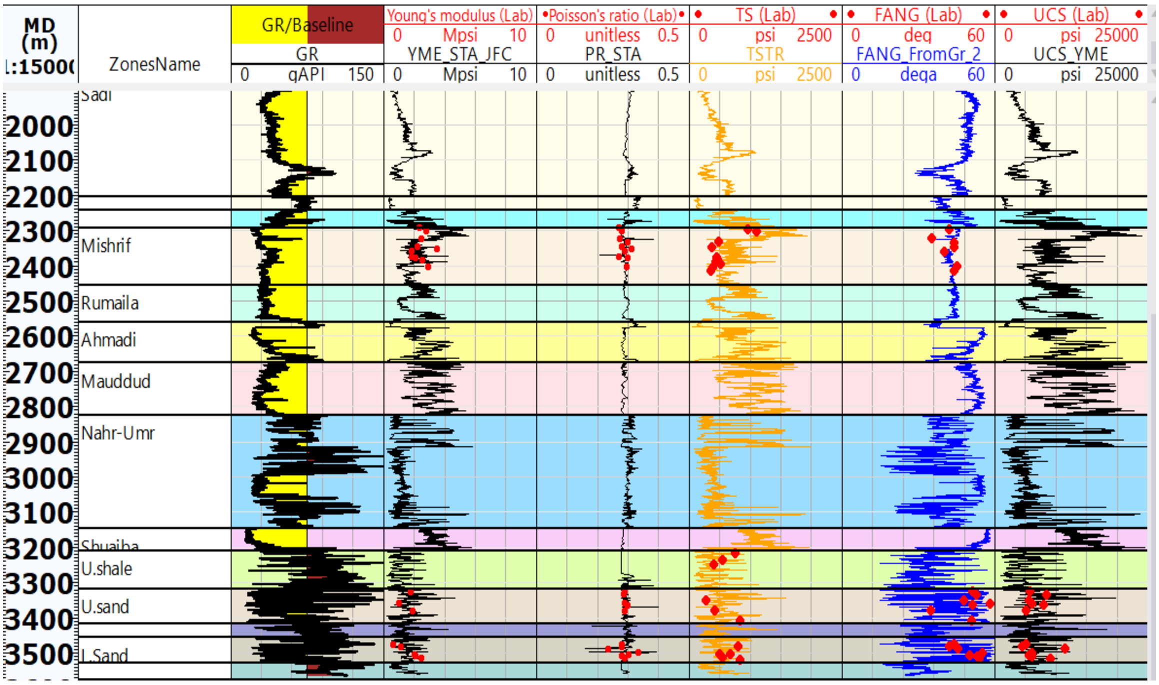
$$vd = \frac{3kd-2Gd}{6Kd+2Gd} \quad (10)$$

Where: E_d: Dynamic Young modulus. G_d: Dynamic Shear modulus. K_d: Dynamic Bulk modulus. V_d: Dynamic Poisson’s ratio. ρb: bulk density in (g/cm^3).

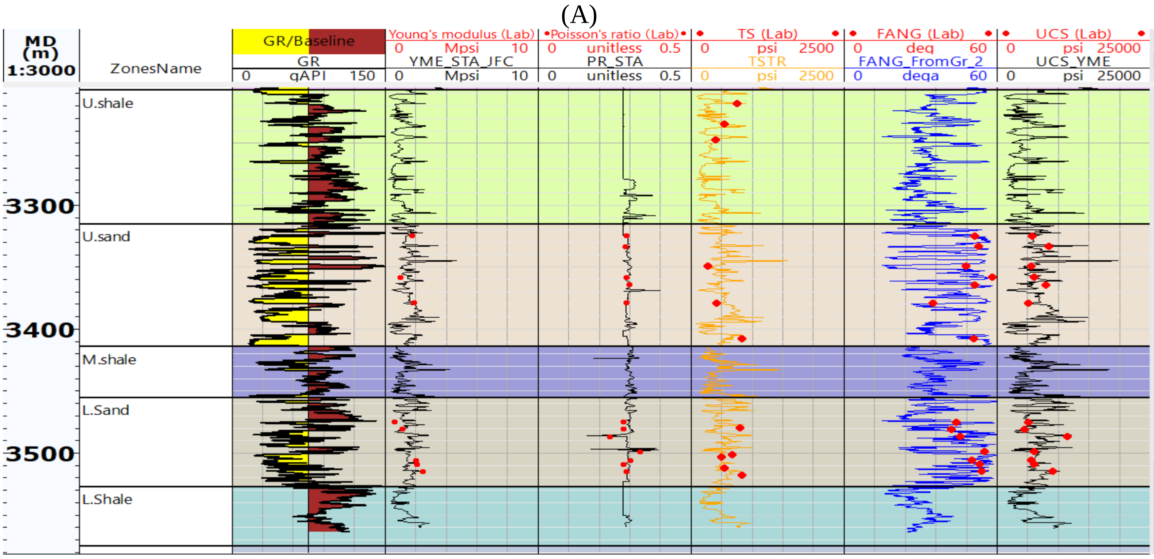
The lab's measurements of rock properties were also plotted in the plot, along with the rock mechanical logs, as can be seen in Fig. 4 (A and B).

3.4. Horizontal stresses magnitude and orientation

The vertical overburden stress action on the rock causes it to move horizontally, affecting the horizontal stresses. In an anisotropic formation with no tectonic activity, horizontal stresses (maximum and minimum) will be equal in magnitude (σH = σh). Otherwise, horizontal stresses will be greater as a result of an active area with faulting or mountains [4].



(A)



(B)

Fig. 4. A) Calculated rock's mechanical properties and laboratory data, B) Calculated rock's mechanical properties and laboratory data

The magnitude and direction of horizontal stresses are critical in many geomechanics problems. Direct approaches such as the leak-off test, the hydraulic fracturing test and the min-frac test can all be utilized to estimate the minimum horizontal stress [16]. For determining horizontal stresses, the poro-elastic horizontal stress model is the most utilized method. The poro-elastic horizontal stress method employs static Young's modulus, Poisson ratio, Biot's constant, overburden stress and pore pressure, as shown in the equations below.

$$\sigma h = \frac{\nu}{1-\nu} * \sigma v - \frac{\nu}{1-\nu} * \alpha Po + \alpha Po \frac{S*\nu}{1-\nu} * \varepsilon h + \frac{E*\nu}{1-\nu^2} * \varepsilon H \qquad (11)$$

$$\sigma H = \frac{\nu}{1-\nu} * \sigma v - \frac{\nu}{1-\nu} * \alpha Po + \alpha Po \frac{S*\nu}{1-\nu} * \varepsilon H + \frac{E*\nu}{1-\nu^2} * \varepsilon h \qquad (12)$$

Where: σh: Minimum horizontal stress. σH: Maximum horizontal stress. υ: Poisson's ratio in static form. E: Young's modulus in static form. α: Biot's coefficient. *Po*: pore pressure.

ε_h and ε_H: Are tectonic strains; they are determined by Eq. 13 and Eq. 14

$$\varepsilon h = \frac{\sigma v*\nu}{E} * \left(1 - \frac{\upsilon^2}{1-\upsilon}\right) \qquad (13)$$

$$\varepsilon H = \frac{\sigma v*\nu}{E} * \left(\frac{\upsilon^2}{1-\upsilon} - 1\right) \qquad (14)$$

Stress orientation is another major factor in geomechanical modeling. Knowledge of stress direction can assist in production, water injection, perforation and completion design [4]. One of the geophysical logs, a four-arm caliper, the Formation Micro Image (FMI) and the micro seismic focal mechanism (modern technology) can be used to determine the stress direction. The caliper and FMI are still the most widely used tools [14]. In well ZB-A, the horizontal stress orientation was determined using interpreted Formation Micro-Imager (FMI) and processed data from the last section 8.5". The orientation of σ_h was at 140 degrees, and σ_H must be perpendicular to σh depending on Anderson's classification, [4, 17], Fig. 5.

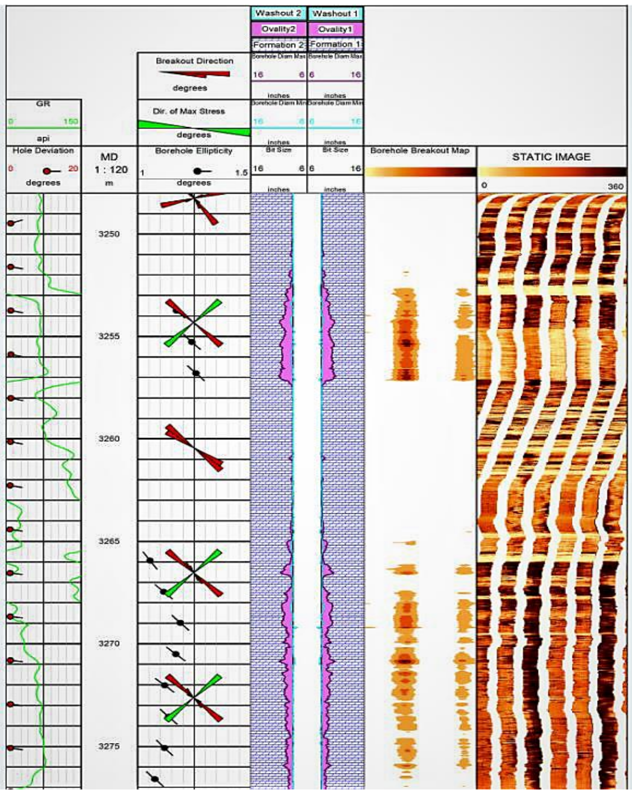


Fig. 5. FMI log for 8.5 in well ZB-A

3.5. Safe Mud window (SMW)

The last step in geomechanical modeling is figuring out the best mud weight for a safe drilling operation. Since shear and tensile failures are the most common types of mechanical problems, a safe mud window is needed to minimize well bore stress while drilling [18]. When the mud weight exceeds expectations, it will enter the rock and cause the formation to fail tensile. On the other hand, a reduced mud weight would cause rock shear failures, often known as borehole breakouts, as seen in Fig. 6 [19].

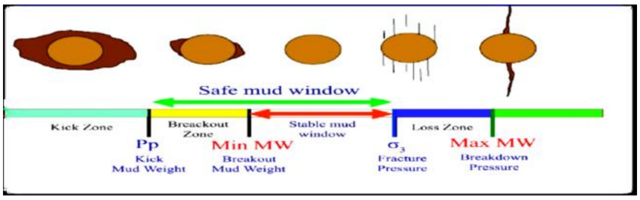


Fig. 6. Mud windows [17]

There are many empirical criteria to predict rock failure. In general, failure criteria are utilized to make failure boundaries that separate stable and safe regions from unstable and failure regions. The failure criteria used to analyze the case study is the Mogi-Coulomb failure criteria [4]. A true triaxial is performed to estimate the (σ_2) as presented in Eq. 16, where τoct is an octahedral shear stress, $\sigma(m,2)$ is the mean effective stress, and f is a nonlinear, power-law function.

$$\tau oct = f(\sigma m, 2) \quad (15)$$

$$\sigma(m,2) = \frac{\sigma 1 + \sigma 2}{2} \quad (16)$$

$$\tau oct = \frac{\sqrt{(\sigma 1 - \sigma 2)^2 + (\sigma 1 - \sigma 3)^2 + (\sigma 2 - \sigma 3)^2}}{3} \quad (17)$$

The octahedral shear stress, the Coulomb strength parameters, and mean stress are formulated as below:

$$\tau oct = a + b\, \sigma m, 2 \quad (18)$$

$$a = \frac{2\sqrt{2}}{3} c \cos \Phi \quad (19)$$

$$b = \frac{2\sqrt{2}}{3} c \sin \Phi \quad (20)$$

Where a and b are strength parameters of Mogi-Coulomb, C is the rock cohesion strength, and ϴ is the internal friction angle in degrees.

Eqs. 21 and 22 were developed to consider the strengthening impact of the intermediate principal stress, where I1 and I2 represent the primary and secondary stress invariants, respectively.

$$I1 = \sigma 1 + \sigma 2 + \sigma 3 \quad (21)$$

$$I2 = \sigma 1\sigma 2 + \sigma 2\sigma 3 + \sigma 3\sigma 1 \quad (22)$$

Now, applying the Mogi-Coulomb criterion:

$$\sqrt{I1^2 - 3I2^2} = a' + b'(I2 - \sigma 2) \quad (23)$$

Where: $a'=2\ c\ cos\emptyset\ and\ b'=sin\emptyset$.

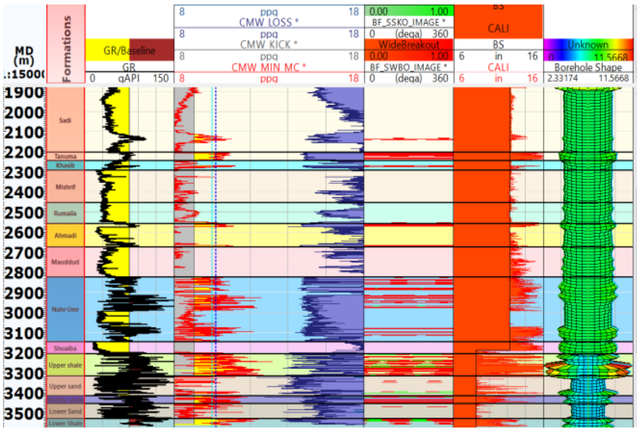
3.6. Single depth sensitivity analysis

The sensitivity analysis uses the generated geomechanics model and well data to estimate the wellbore stability across the hole orientation at a selected single depth. There are two outputs for this kind of analysis that will be considered during this study:

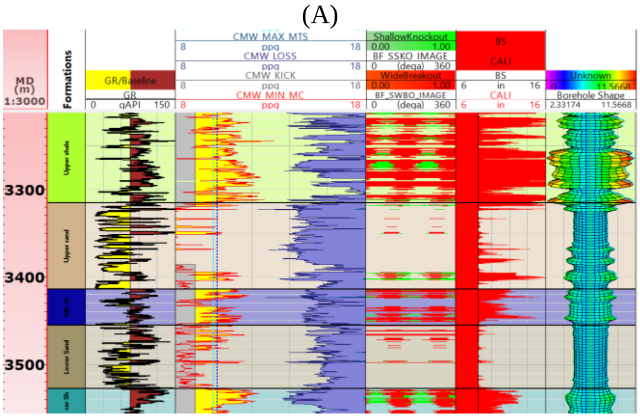
1-Breakout vs. Orientation Polar Plot: The plot provides the minimum mud weight as a function of borehole azimuth and inclination.
2-Breakdown vs. Orientation Polar Plot: This plot shows the maximum mud weight as a function of the well's azimuth and inclination.

4- Results and discussion

Mogi-Coulomb failure criteria have been applied to obtain the results shown in Fig. 7 A and Fig. 7 B. The first three tracks show the well depth, formations and GR. The fourth track shows the mud weight window. It will be split into four parts. The gray part will show the kick area, and the yellow part will show the breakout area. On the opposite side, it reveals the area where drilling mud is lost and the fracture that is caused when the amount of mud used is more than the blue profile. So, the area in the middle, which is colored white, is the mud weight window, which can be used to drill into the Zubair formation. The fifth truck represents the failure area predicted by the Mogi Coulomb failure criterion. The sixth track was added for validation to check if the failure criterion predicted the right failure placed by comparing it to the bit size and caliber logs combined to check the breakout places, and the sixth truck shows the borehole shape and where the enlargement places. Most of the failure places were predicted accurately by the mechanical earth model, especially in the upper, middle, and lower shale sections, which have the most nonproductive time in the drilling operations.



(A)



(B)

Fig. 7. a) Wellbore failure using Mogi Coulomb method, b) Wellbore failure using Mogi Coulomb method

The sensitivity analyses were done on the three layers of shale in the Zubair Formation: the upper shale, the middle shale, and the lower shale. The selected depths are chosen in the severely affected points and in the middle of each unit, which are at 3279 m, 3445 m, and 3534 m. Furthermore, these points are not the only ones that have instability problems, but they were selected for illustration (Fig. 7 A and Fig. 7 B). The breakdown polar plot shows that the higher breakdown limit is in the direction of the minimum horizontal stress when the inclination ranges between 0° and 50° (Fig. 8, Fig. 9, and Fig. 10). On the other hand, the breakout polar plot illustrated that the safe mud weight window becomes smaller at deviation more than 40° and in all directions.

The mud weight window that ranged between 1.33 g/cc to 1.68 g/cc in upper shale for middle shale ranges between 1.3 g/cc to 1.63 g/cc, while it is 1.31 g/cc to 1.7 g/cc in lower shale when the well inclination is between 0° and 20°. In all three layers, the mud weight starts to narrow when the inclination increases above 20° until it becomes critical above 50° inclinations. Fig. 8, Fig. 9, and Fig. 10 show the polar plot for upper, middle, and lower shale, respectively.

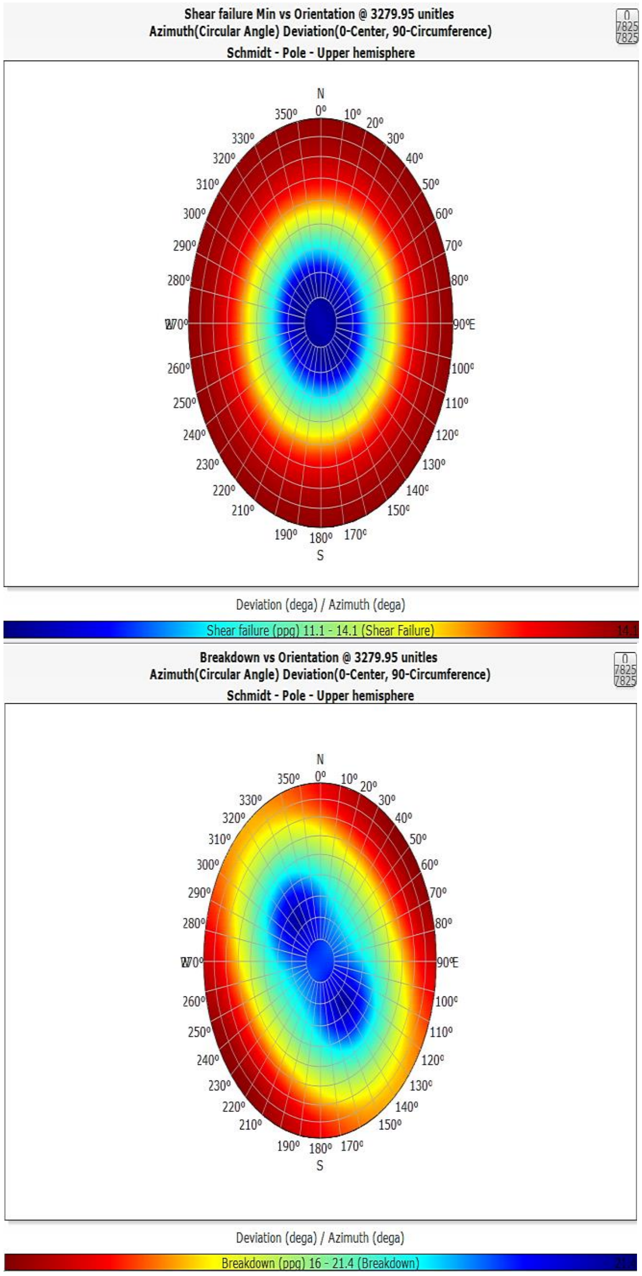


Fig. 8. Shear failure and tensile failure polar plot analysis for Zubair/Upper Shale at depth 3279 m

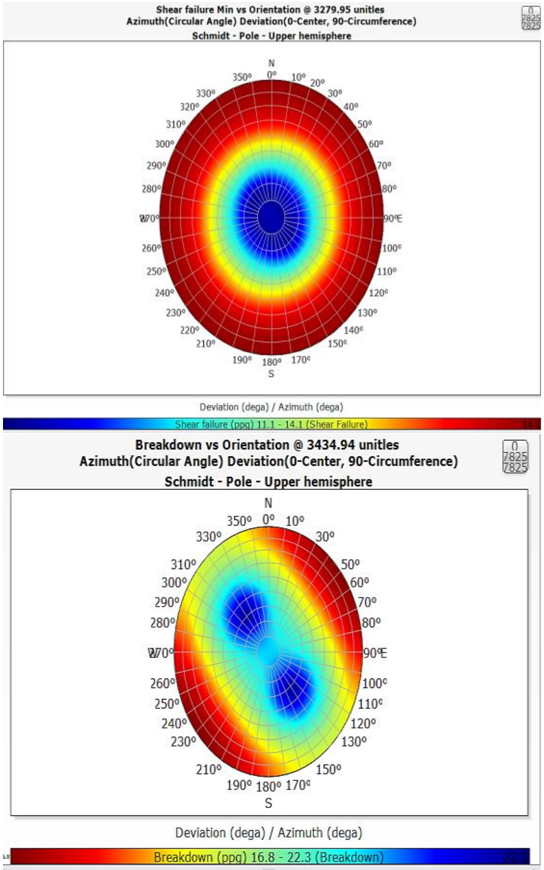


Fig. 9. Shear Failure and Tensile Failure Polar Plot Analysis for Zubair/Middle Shale at Depth 3434 m

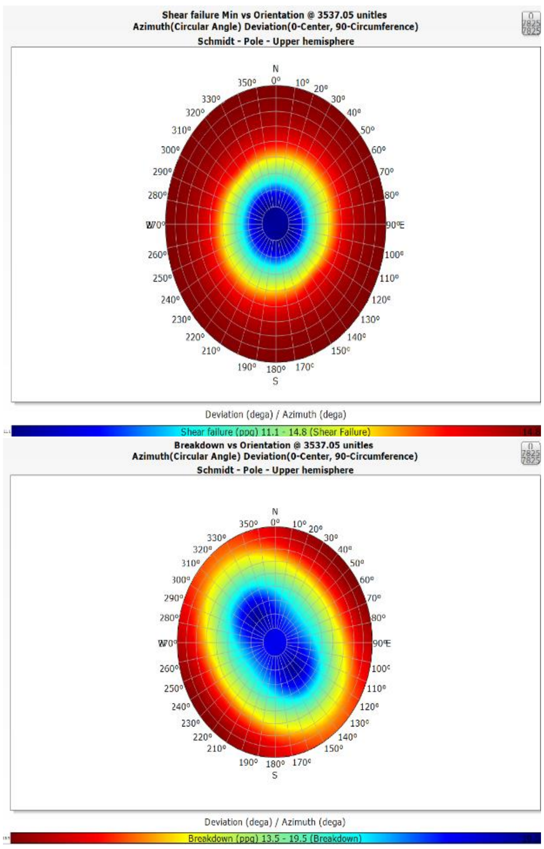


Fig. 10. Shear Failure and Tensile Failure Polar Plot Analysis for Zubair/Lower Shale at Depth 3534 m

5- Conclusions

This study presents a 1-D mechanical earth model to figure out the issues related to wellbore instabilities in the Zubair formation, Zubair oilfield. Based on the outcomes, 1.35 g/cc is the optimum mud weight for drilling the Zubair formation, which will allow for safe drilling operations with minimum shear rock failure. It was also found that the tectonic regime in the Zubair Formation corresponds to the category of normal stress regime. The outcome of the sensitivity analysis that was conducted against Zubair formation revealed that the vertical wells or wells with low deviation angles (up to 50 degrees) are less likely to have instability issues than wells that have high deviation angles (beyond 50 degrees). The direction of drilling should be normal to the bedding planes of the formation as well as perpendicular to the direction of the minimum horizontal stress.

Nomenclature

1D-MEM: One-dimensional mechanical earth model.
BS: Bit size log.
CAL: Caliber log.
DTC: Compressional sonic log.
DTS: shear sonic log.
LOT: Leak off test.
MEM: Mechanical earth model.
MW: Mud weight.
NPT: None productive time.
QRA: Quantitative risk assessment.
RFT: Repeated formation tester.

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النمذجة الجيوميكانيكية ونهج تحليل استقرار الآبار لدراسة سلوك تكوينات الصخور الطينية

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الخلاصة

يعد استقرار حفرة البئر أحد المشكلات الرئيسية في زيادة الوقت غير المنتج (NPT)، مما سيزيد من التكاليف المنفقة وبالتالي خسائر الإيرادات. من المرجح أن تسبب التكوينات الصخرية مشاكل عند الحفر من خلالها أكثر من غالبية التكوينات الصخرية.، كما أن عدم استقرار الصخر الزيتي هو سبب حوالي ٧٥٪ من مشاكل الآبار. لذلك تم تطبيق تحليلات جيوميكانيكية متقدمة على آبار مختارة في حقل الزبير النفطي بسبب نقص مثل هذه الدراسات في هذا المجال. في هذا البحث، تم بناء النموذج لبئرين (ZB-A وZB-B) باستخدام بيانات سجل البئر المتاحة مثل حجم الحفارة (BS) والعيار (CAL) والقص (DTS) والضغط (DTC) الصوتي واشعة كاما (GR). تمت معايرة الحد الأدنى من الضغط الأفقي باختبار التسرب (LOT) بينما تمت معايرة ضغوط المسام بقياسات ضغط المسام من اختبار التكوين المتكرر (RFT). تم استخدام نتائج النموذج لإجراء تحليل استقرار حفرة البئر. يركز هذا الجزء على حساب نافذة طين التشغيل الآمن لتحديد وزن الطين باستخدام معايير فشل معينة. تم استخدام معايير فشل Mogi–Coulomb للعثور على نافذة وزن الطين اللازمة للحفر المتوازن. توفر دراسة الحالة أن النطاق لوزن الطين كان بين 1.32 غرام / سم مكعب و١,٤٥ غرام / سم مكعب. بينما تم استخدام ١,١٩ غرام / سم مكعب أثناء الحفر. يمكن استخدام نتائج هذا البحث كدليل لاختيار أفضل وزن طيني لحل المشكلات المتعلقة باستقرار آبار الآبار في هذا المجال.

الكلمات الدالة: الصخور الطينية، طبقة الزبير، فشل الصخور الطينية، تحليل الحساسية لعمق واحد، جيوميكانيك، عدم استقرار البئر.