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Geomechanical Analysis to Avoid Serious Drilling Hazards in Zubair Oilfield, Southern Iraq

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Abstract

Zubair oilfield is an efficient contributor to the total Iraqi produced hydrocarbon. Drilling vertical wells as well as deviated and horizontal wells have been experiencing intractable challenges. Investigation of well data showed that the wellbore instability issues were the major challenges to drill in Zubair oilfield. These experienced borehole instability problems are attributed to the increase in the nonproductive time (NPT). This study can assist in managing an investment-drilling plan with less nonproductive time and more efficient well designing.

To achieve the study objectives, a one dimension geomechanical model (1D MEM) was constructed based on open hole log measurements, including Gamma-ray (GR), Caliper (CALI), Density (RHOZ), sonic compression (DTCO) and shear (DTSM) wave velocities, and Micro imager log (FMI). The determined 1D MEM components, i.e., pore pressure, rock mechanical properties, in-situ principal stress magnitudes and orientations, were calibrated using the data acquired from repeated formation test (RFT), hydraulic fracturing test (Mini-frac), and laboratory rock core mechanical test (triaxial test). Then, a validation model coupled with three failure criteria, i.e., Mohr-Coulomb, Mogi-Coulomb, and Modified lade, was conducted using the Caliper and Micro-imager logs. Finally, sensitivity and forecasting stability analyses were implemented to predict the most stable wellbore trajectory concerning the safe mud window for the planned wells.

The implemented wellbore instability analysis utilizing Mogi-Coulomb criterion demonstrated that the azimuth of 140° paralleling to the minimum horizontal stress is preferable to orient deviated and horizontal wells. The vertical and slightly deviated boreholes (less than 30°) are the most stable wellbores, and they are recommended to be drilled with 11.6 -12 ppg mud weight. The highly deviated and horizontal wells are recommended to be drilled with a mud weight of 12-12.6 ppg.

Keywords: Geomechanical analysis; Wellbore Stability; Zubair Oilfield.

تحليلات جيوميكانيكية لتجنب مخاطر الحفر الحرجة في حقل الزبير النفطي جنوب العراق

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الخلاصة:

يعتبر حقل الزبير من الحقول المساهمة بفعالية في الانتاج الكلي للنفط العراقي . لكن حفر الابار العمودية او المائلة في هذا الحقل يواجه تحديات معقدة جدا , وقد اظهر استقصاء بيانات الابار المحفورة في حقل الزبير ان مشاكل عدم استقرارية جدار البئر تشكل الجزء الاكبر من معوقات حفر الابار في الحقل وقد

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تسببت بزيادة الزمن المستهلك لإتمام عمليات الحفر. هذه الدراسة ممكن ان تساهم في ادارة خطة حفر لاستثمار الحقل باقل استنزاف للزمن و تصميم اكثر كفاءة للآبار المخططة. لتحقيق اهداف الدراسة تم بناء موديل جيوميكانيكي احادي الابعاد باستخدام القاسيات الحقلية لمجسات الابار (Micro imager log (FMI) , Density (RHOZ) , Caliper (CALI) , Gamma-ray (GR) , ومعاييرة عناصر الموديل الجيوميكانيكي و التي تتألف من ضغط الطبقة, الصفات الميكانيكية للصخور, و قيم واتجاه الاجهادات الصخرية باستخدام فحوصات الباب المختبرية (Traixial test) والبيانات الحقلية المتحصله من الفحوصات الضغط و التشقيق الهاديروليكي (RFT , Mohr- Mini-frac) . ثم اجراء تحليل لاستقرارية جدار البئر باستخدام معايير التنبئ بانهييار الصخور (Mohr- coulomb , Mogi-Coulomb, Modified Lade) لاثبات فاعلية الموديل الجيوميكانيكي مع معيار الانهييار الانسب . و اخيرا, تنفيذ تحليل حساسية الاستقرارية و تحليل الاستقرارية المستقبلي للتنبئ بافضل مسار و كثافة طين للآبار المخططة. أظهر تحليل عدم استقرار حفرة البئر باستخدام معيار Mogi-Coulomb أن امالة تجويف البئر باتجاه 140 درجة بموازات الإجهاد الأفقي الأدنى يعتبر الأفضل لحفر الآبار المائلة والأفقية. وان الابار العمودية والقليلة الميل (اقل من 30 درجه) هي الأكثر استقرارا ويوصى بحفرها بكثافة طين 11.6-12 ppg. اما الابار الأفقية و شديدة الميل فيوصى بحفرها بكثافة طين 12-12.6 ppg.

1- Introduction

Zubair is one of the hugest and most challenging oilfields in the world. The field is a crucial partner in Iraqis total oil production. The main efficient hydrocarbon-bearing reservoirs in Zubair oilfield are Mishrif and Zubair formations. The exploitation of these reservoirs for production necessitates drilling through an interval of thick hazardous succession of carbonate and clastic layers. This interval is frequently reported as the most risky interval to drill. The most complex sort of the encountered problems is categorized as the wellbore instability dilemmas that contribute to the majority of the non-productive time (NPT) consumed to drill in Zubair oilfield. Minimizing the relatively high cost attributed to the instability issues can be managed by conducting an integrated geomechanical analysis. Determining the mechanical earth model components is the primary input for the rock mechanical analysis [1]. Pore pressure, rock mechanical properties, in-situ stress are the principal components of the geomechanical model [2]. The main controllable parameters of geomechanical analysis outputs are the mud weight window and the wellbore trajectory that can be optimized to mitigate the shear and/or tensile wellbore failure [3].

Shear and/or tensile failure is caused by the disturbance of far-field stress around the wellbore due to drilling operations. Shear failure (breakouts) occurs when the borehole rock compressive strength is exceeded by the concentration of drilling-induced stresses around the wellbore, because of the insufficient drilling fluid support to the wellbore wall. Hence, mud weight should be increased to be higher than the shear failure pressure to avoid the borehole enlargement or elongation that can lead to poor-quality cement bond and log measurements, tight hole, wellbore collapse, stuck pipe, and logging tools, which may, in turn, entail fishing and/or side-tracking. However, excessively increased mud weight can cause drilling-induced tensile fractures that can develop to hydraulic fractures as the wellbore pressure exceeds the minimum horizontal stress. Then, the mud pressure should not be higher than the maximum breakdown pressure and the minimum horizontal stress to avoid the occurrence of mud loss, differential sticking, and lost circulation. Shear failure was the major contributor to the investigated wellbore instability dilemmas as demonstrated by Mohammed's (2017) geomechanical analysis for Nahr Umr formation in a southern Iraqi oilfield [4]. Abbas *et al.*, (2018) concluded that the mud weight used to drill Zubair formation in an Iraqi southern oilfield was insufficient to support the borehole wall against the experimented shear failure [5].

This study can contribute to minimize the NPT and the costs for safely drilling vertical and deviated wells in Zubair oilfield by conducting an integrated geomechanical analysis to mitigate the investigated wellbore instability problems.

1-1 Breakdown time analysis for the investigated interval

Surveying the offset wells drilling on a daily basis and final reports demonstrated that the most unstable interval extended from the Sadi crest to the end of the lower shale layer form Zubair

formation, which constitutes about 47% of the total footage. Drilling this interval, which is composed of the 12¼ and 8½ sections, consumed about 64% of the total drilling time? The nonproductive time due to instability problems constituted about 56% (16% for 12¼ and 40% for 8½) of the total time consumed to drill these sections, as shown in Figure-1. The majority of the observed unstable issues were pipe and logging tool sticking, tight hole, and shale caving that caused fishing and sidetracking at the worst conditions. Therefore, the high percentage of instability and nonproductive time for these two sections, as opposed to the total drilling and nonproductive time, was the motivation to apply a geomechanical analysis to mitigate the nonproductive time by proposing a stable mud window and wellbore trajectory for the wells that are planned to drill in the oilfield.

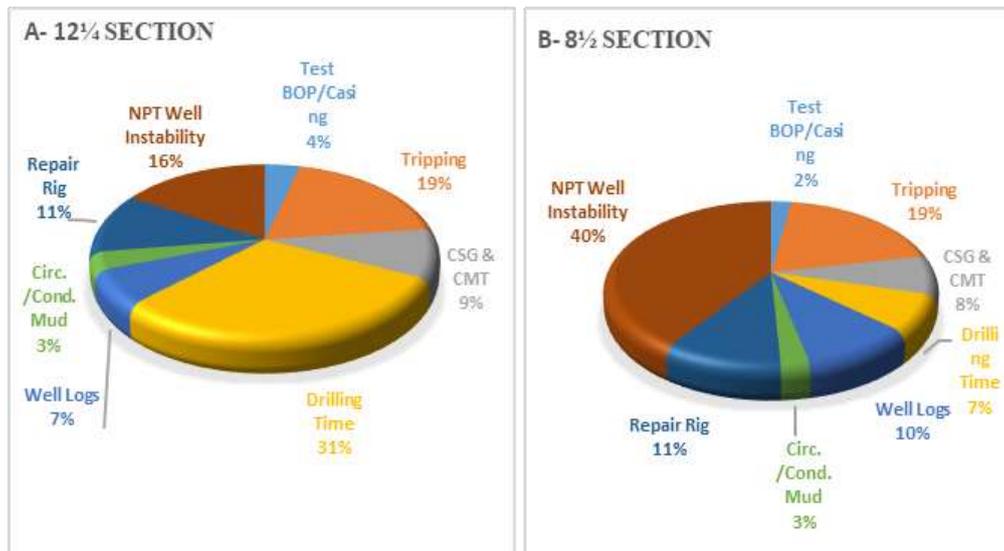


Figure 1- Breakdown time for the 12¼ and 8½ sections drilled in Zubair oilfield.

2- Methodology

An integrated methodology was executed to perform an accurate geomechanical analysis, as introduced in Figure-2. First, the collected data was audited to confirm its validity. Second, a comprehensive one dimension mechanical earth model (1D MEM) was constructed employing the log data acquired from the vertical well (A), i.e., Gamma-Ray log (GR), Density log (RHOZ), and sonic compression (DTCO) shear (DTSM) wave velocities, and micro-imager logs. Third, the estimated profiles of the 1D MEM constituents, i.e., pore pressure, rock mechanical properties, and far-field stress magnitudes and orientation, were calibrated using the acquired data from repeated formation test (RFT), core rock mechanical laboratory test (triaxial test), and hydraulic fracture test (Mini-frac). Fourth, validating was performed for the built geomechanical model coupled with the three failure criteria (Mohr-Coulomb, Modified lade, and Mogi-Coulomb) by comparing the predicted wellbore failure to the actual observed borehole failure from Caliper (CALI) and formation micro imager log (FMI). Finally, the single depth sensitivity analysis and forecasting wellbore stability analysis using the most convenient failure criterion (Mogi-Coulomb criterion) were conducted to identify and plan the most stable wellbore trajectory concerning the mud window.

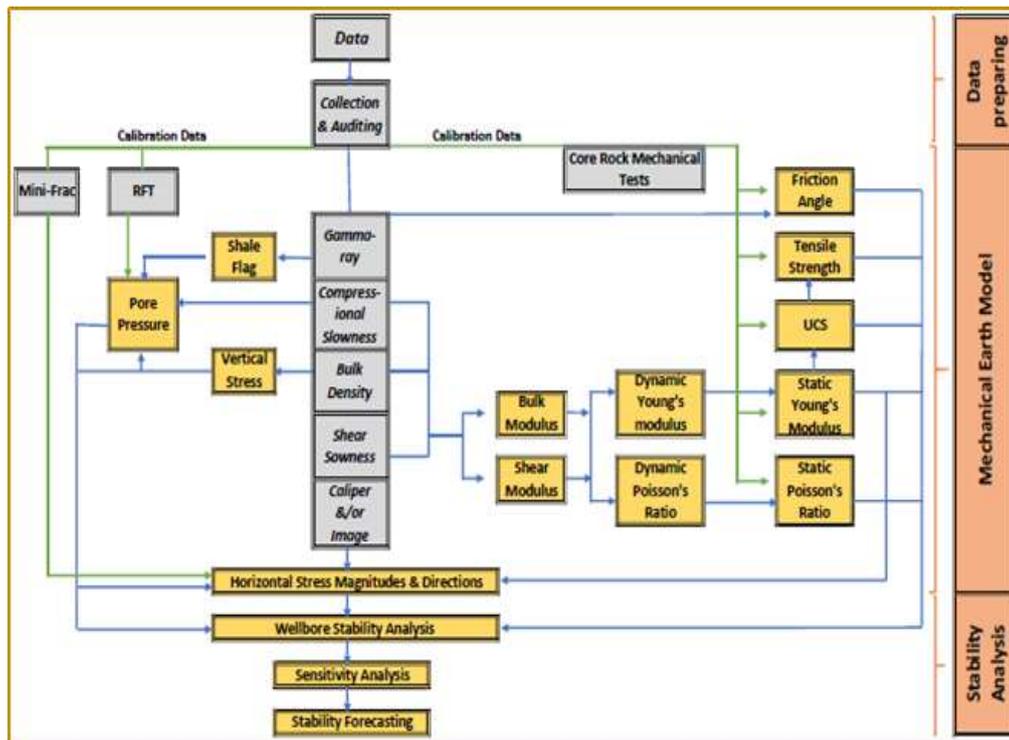


Figure 2-Workflow of the study methodology.

3- Geomechanical modeling

A comprehensive geomechanical model that is essentially comprised of overburden stress, mechanical stratigraphy, pore pressure, rock elastic and strength properties, and orientations and magnitudes of horizontal stresses was developed with managing the best exploitation of available field geomechanics related data.

3-1 Vertical stress magnitude

The vertical stress is one of the most essential input parameters in any mechanical earth modeling. The vertical stress is fundamentally attributed to the weight of both overlaying formations and the fluid they confined [6]. The overburden stress was computed by integrating the densities extracted from the Bulk Density log (RHOZ) that covered rocks from Sadi to the end of Zubair formation, using equation (1) [7].

$$S_v = \int_0^z \rho(z) dz \tag{1}$$

where ρ is the bulk density of the overlaying rock integrated with respect to the depth of interest (z), and g equates the gravity acceleration (m/s^2).

While the intervals of missing density to the surface are extrapolated employing the equation (2) [8, 9].

$$\rho_{extrapolated} = \rho_{mudline} + A_0 \times (TVD - Air\ Gap)^\alpha \tag{2}$$

where ρ_{mud} is the density at ground level (soil density 1.65 gm/cm^3), Air Gap is Rig floor height from the ground level (m), TVD is the true vertical depth (m), and A_0 and α are Fitting parameters. The computed overburden stress ranges from 0.95 to 1.00 psi/ft, as illustrated in the seventh track from Figure-3.

3-2 Mechanical Stratigraphy

Stratigraphy is an inspection of the succession and time-related construction of rock strata. Sorting the rocks based on their mechanical stratigraphy enables to specify the appropriate correlations for the varied formations lithology for best estimation of their geomechanical parameters. The differentiation of shale from non-shale was fulfilled by setting a value of 75 gAPI thresholds for the gamma-ray logs, which was identical to mud log reports and revealed good agreement with calibrating pore pressure points extracted by formation tester technique from permeable layers, since no pressure point lies on a shale zone, as presented in the third track from Figure-3.

3-3 Pore Pressure

Prediction of pore pressure is an essential constituent in the mechanical earth modeling. It is a crucial mechanical parameter that is vitally used to estimate the magnitudes of the in-situ horizontal principal stresses and to predict a safe mud weight window for drilling a stable wellbore [10]. The profile of pore pressure was computed by combining the profiles of normal and geo-pressures. The normal pressure (Hydrostatic pressure, P_h) profile was calculated utilizing equation (3) [11] based on an average formation water density (ρ_w) of 1.0772 (gm/cm³). The geo-pressure profile was estimated using the method proposed by Eaton (1969) that was derived based on slowness measurement [12]. The equation numbered (4) was formulated from sonic compressional wave velocity (DTC) with a semi-logarithmic normal trend line for shale zones, while the calculated hydrostatic pressure was assigned for the non-shale zone [9, 10, 13]. There was a reasonable correspondence between the estimated pore pressure profile and the individually RFT measured data in the lower part of Mishrif, Nahr Umr, and Zubair lower sand intervals, as shown in the seventh track from Figure-3. Since Eaton's method does not consider the pore pressure depletion due to production, the deviation of the RFT measured points in the upper part of Mishrif and Zubair upper Sand layers from the estimated pore pressure profile is reasonable.

$$P_h = \int_0^z \rho_w g dz \quad 3$$

$$P_{pg} = OBG - (OBG - P_{hg}) \left(\frac{NCT}{DT} \right)^3 \quad 4$$

where P_{pg} donates to the gradient of pore pressure, OBG represents the gradient of overburden, P_{hg} is the normal pore pressure gradient (the hydrostatic pressure), NCT refers to the normal compacted trend line that is fitting to the compressional wave log measurements, and DT is the compressional transit time.

3-4 Rock mechanical properties

Elastic parameters (Young's Modulus and Poisson's ratio) and compressive and tensile strength parameters (unconfined compressive strength, angle of internal friction, and tensile strength) are the main rock mechanical properties. These properties are essential parameters in stress determination, wellbore stability analysis, and the prediction of optimum mud window for stable drilling. The direct laboratory methods to measure the rock mechanical properties are commonly used to calibrate the estimated profiles of these properties using indirect petrophysical methods.

The sonic model that is derived based on the Bulk density (RHOZ) and shear DTS and DTC slowness velocities, as formulated in equations (5) and (6), was used to estimate the shear (G) and bulk (K) moduli [9, 14], which were in turn employed to compute the Young's modulus and Poisson's ratio. Equations (7) and (8) were used to compute the dynamic profiles of Young's modulus and Poisson's ratio [9, 15]. The static form of Young's modulus typifies the more realistic profile and always being lower than the dynamic profile due to the influence of cementation, pore pressure, amplitude and rate of stress-strain [16]. Consequently, John Fuller's correlation was utilized to compute the profile of static Young's Modulus [9]. Static Poisson's ratio was considered equivalent to the dynamic form as commonly applied in rock mechanics [17]. The computed static profiles exhibited good agreement with the direct measurements from laboratory triaxial test, as illustrated in the fourth track from Figure-3.

$$G_{dyn} = 13474.45 \frac{\rho_b}{\Delta t_{shear}^2} \quad 5$$

$$K_{dyn} = 13474.45 \rho_b \left(\frac{1}{\Delta t_{comp}^2} \right) - \frac{4}{3} G \quad 6$$

where ρ_b is the Bulk density of the formation in gm/cm³ obtained from density log. Δt_{shear} and Δt_{comp} are shear and compressional acoustic travel time in $\mu\text{sec}/\text{ft}$. 13474.45 is the unit's conversion coefficient.

$$E = \frac{9G \cdot K}{G + 3K} \quad 7$$

$$\nu = \frac{3k - 2G}{6k + 2G} \quad 8$$

where E represents Young's modulus measured in Mpsi, and ν refers to the unit less Poisson's ratio.

As for the strength mechanical properties, the static Young's modulus correlations were designated to determine the unconfined compressive strength (UCS) profile as a function of Young's modulus [9]. Then, tensile strength profile was determined as a function of UCS [9]. The angle of internal friction profile was estimated using a correlation that maps Gamma-ray (GR) to the internal friction angle with a linear relation [9]. The determined profile of the rock mechanical strength parameters displayed an acceptable match to the direct measurements of the core laboratory triaxial test, as explained the fifth and sixth tracks from Figure-3.

3-5 Horizontal stress magnitudes and orientations

The principal horizontal stress values are essential inputs to rock mechanical analysis. The magnitude of maximum horizontal principal stress is considered the most complex element for determining the stress tensor [7]. Although there are different indirect methods to determine both minimum (S_{Hmin}) and maximum (S_{Hmax}) horizontal stress magnitudes, there is only one direct method to measure the minimum horizontal stress magnitudes such as leak-off test, Mini-frac test, and micro-frac test.

The poro-elastic constitutive model is the most successfully utilized method for the determination of horizontal stress magnitudes. Flat-layered poro-elasticity deformation was supposed in the formation rock to set a couple of specific constant strains, i.e. ϵ_y and ϵ_x , for the formation in the directions of maximum and minimum horizontal stresses, respectively [9, 16]. For a fluid-saturated porous material, the poro-elastic horizontal strain model was introduced by Thiercelin and Plumb (1994), considering anisotropic tectonic strains and isotropic linear elasticity, to estimate the horizontal stress magnitudes (S_{Hmin} and S_{Hmax}) continuously along the wellbore utilizing equations (9) and (10) [14, 18].

$$\sigma_h = \frac{\nu}{1-\nu} (\sigma_v - \alpha P_p) + \alpha P_p + \frac{E_{sta}}{1-\nu^2} (\epsilon_x + \nu \epsilon_y) \quad 9$$

$$\sigma_H = \frac{\nu}{1-\nu} (\sigma_v - \alpha P_p) + \alpha P_p + \frac{E_{sta}}{1-\nu^2} (\epsilon_y + \nu \epsilon_x) \quad 10$$

where σ_h and σ_H denote minimum and maximum horizontal stresses. ν represents Poisson's ratio. σ_v refers to the vertical in-situ stress. α indicates Biot's coefficient (conventionally $\alpha=1$). E_s is static Young's modulus. P_p is pore pressure. ϵ_x and ϵ_y are a strain in σ_h and σ_H directions, respectively, as given in equation equations (11) and (12) [118, 19]:

$$\epsilon_y = \frac{\sigma_v \nu}{E} \left(1 - \frac{\nu^2}{1-\nu} \right) \quad 11$$

$$\epsilon_x = \frac{\sigma_v \nu}{E} \left(\frac{1}{1-\nu} - 1 \right) \quad 12$$

An iteration method was implemented for strain constants until accomplishing a reasonable match between the indirectly obtained profile and the Mini-frac direct measurement of minimum horizontal stress.

Processed and interpreted Micro-imager (FMI) data were surveyed to identify the direction of horizontal far field stresses (Figure-4). Investigation of 45 distinct zones indicated that the shear failure developed at an orientation of 140° , with standard deviation of 10° . Consequently, the minimum horizontal stress direction was set at 140° (Figure-4). The orientation of maximum horizontal stress was set at 50° since it was approved to be perpendicular to the orientation of the minimum horizontal stress.

The construction of geomechanical model was accomplished by determining the vertical stress (VERTICAL_EXE), pore pressure (PPRS_EATONS), rock mechanical properties (i.e., Young's modulus (YME_STA_JFC), Poisson's ratio (PR_STA), UCS (UCS_YME), tensile strength (TSTR), angle of internal friction (FANG_FromGr)), and horizontal stress magnitudes (SHMAX_PHS and SHMIN_PHS), as presented in Figure-3.

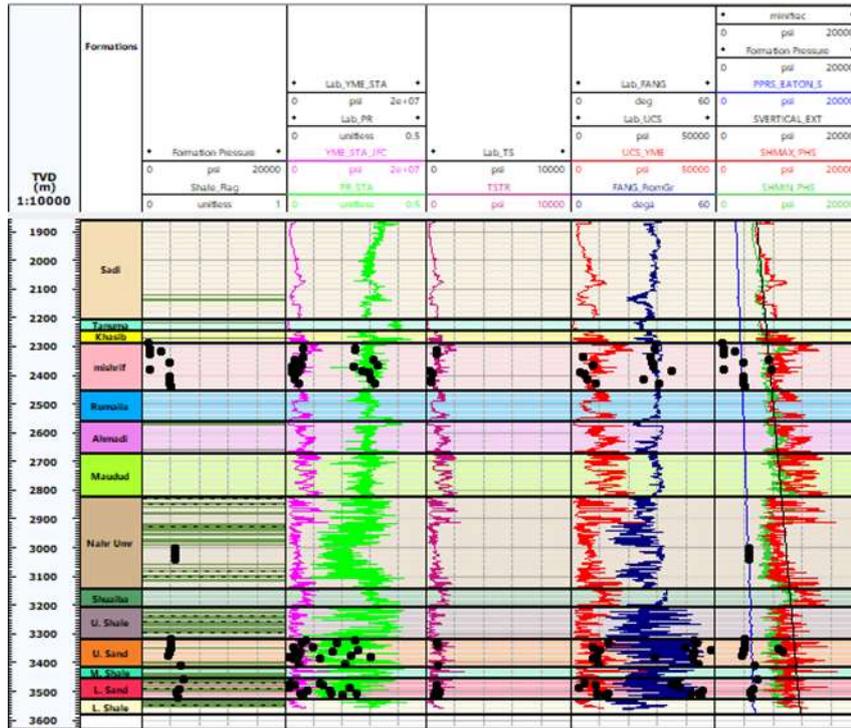


Figure 3-Components of the constructed geomechanical model.

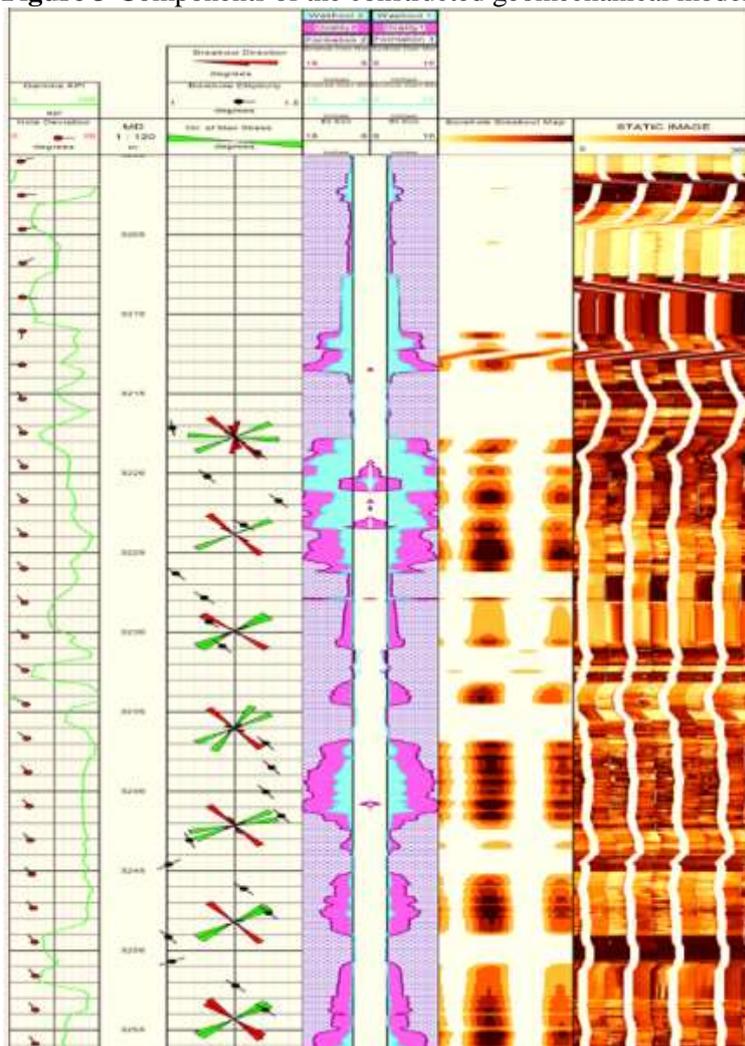


Figure 4-Interpreted micro-imager log.

4- Wellbore stability analysis

3-1 Model validation

The validity of the constructed geomechanical model has to be verified, before being applied, by conducting a failure match under the actual mud weight conditions. The failure match is conducted by comparing the predicted borehole instability with actual wellbore failure displaced by the micro-image log and/or caliper log. The failure criterion that reveals the higher level of compatibility is considered the most suitable criterion for the interval of interest.

The most widely applied failure criteria in geomechanical (i.e., Mohr-coulomb, Mogi-Coulomb and modified Lade) were utilized to predict the unstable regions in the wellbore drilled with 10 ppg mud weight along with the selected interval. Evaluating the predicted failure with respect to the caliper, Micro-image log and drilling events revealed that the Mohr-coulomb was too exaggerate while the modified lade was conservative to predict the shear failure. In contrast, Mogi-Coulomb had a more compatible and moderately predicted rock failure compared to the others.

3-2 Single depth sensitivity-analysis

The sensitivity analysis assists drilling engineers to identify the proper well trajectory that is compatible with the constraints of the well designing. This analysis was implemented at critical depths (i.e., 2138, 2225, 2270, 2255, 2670, 2885, 3270, 3435, 3495 and 3535m) from all hazardous layers that are comprising the interval of interest from Zubair field, assigning Mogi-Coulomb criterion with the earlier constructed MEM under the condition of current mud weight (10 ppg). The sensitivity analysis outcomes revealed that the wells that deviate with an inclination ranging between 0° and about 40° are the most stable. The safe mud weight window tends to narrow for inclinations above 30 degrees. The preferred orientation for the deviated and horizontal wells is longitudinal to the minimum horizontal stress with a deviation of less than 40° for wider mud window and more stable wells. However, drilling highly deviated or horizontal wells in the direction of minimum horizontal stress is possible with a careful designing for breakout and breakdown mud weights.

3-3 Wellbore stability forecast (development plan)

The borehole stability forecasting is performed for an assigned borehole trajectory to predict the severity of the shear and tensile failures along with the interval of interest. The forecasting outcomes are employed to improve the wellbore designing for the planned wells to drill in the studied well's surrounding region. In the present study, the borehole stability forecasting was executed for different wellbore trajectories graduated from vertical to horizontal borehole along an azimuth parallels to the orientation of minimum horizontal stress (140°). The planned inclination was designated considering the conducted single depth sensitivity analysis and the inclination angle effect on the carrying capacity. The aim was to determine the sensible proper mud weight window and assess potential drilling risks to reduce the risks-related instability of the wellbore that recoded from surrounding wells. This was achieved by employing the built geomechanical model and using Mogi-Coulomb criterion. The selected inclinations and the results of wellbore stability forecast are presented in Table-1.

Table 1-Planned wellbore trajectory versus required stable mud weight

No	Inclination (Degree)	Azimuth (Degree)	Mud weight (ppg) MIN_MW – MAX_MW
1	0° (vertical)	140°	11.6 - 12.0
2	30°	140°	11.6 - 12.0
3	40°	140°	12.2 - 12.4
4	50°	140°	12.3 - 12.5
5	60°	140°	12.4 - 12.6
6	88° (horizontal)	140°	12.4 - 12.6

Table-1 shows that the mud weight required to stabilize the wellbore increases with increasing the wellbore inclination angle. The MIN_MW is the proposed mud weight for a specified inclination and the MAX_MW is the mud weight when taking in consideration the equivalent circulation density (ECD), where the vertical wellbore and wellbore deviated to 30° required the same mud weight to

control shear failure. We should bear in mind that the selected mud weight was designed to cause no tensile failure and reduce shear failure as low as possible.

5- Conclusions

The work was conducted for investigating the rock mechanical features of the interval extended from Sadi crest to the end of the lower shale from Zubair formation in Zubair oilfield to optimize the mud weight window and wellbore trajectory for wells drilling plan. The following conclusions were made:

- 1- The reasonable agreement between the laboratory tests and the static correlations utilized in this study to estimate rock mechanical properties validated the correlations for the carbonate and clastic rock columns that are consisted of the formation along with the studied interval from Zubair oilfield.
- 2- Comparing the determined principal horizontal stress magnitudes to the overburden stress magnitude showed that the carbonate rocks endure a strike-slip faulting tectonic regime, whereas the clastic rocks undergo a normal slip faulting regime.
- 3- Based on the sensitivity analysis, the optimal orientation to direct the deviated and horizontal wells is longitudinal to the direction of the minimum horizontal stress at 140° .
- 4- Increasing mud weight from 10 ppg to 12 ppg for the vertical and slightly deviated wells and increasing mud weight to 12.6 ppg for highly deviated and horizontal well will overcome the instability shear failure along with the studied interval.
- 5- The wellbore instability analysis for real failure, observed from image log and predicted failure using Mogi-Coulomb, revealed that only shear failure was experienced using current and proposed mud weight.
- 6- The forecasting analysis proved that the vertical and slightly inclined wells (less than 40°) are more stable than the highly deviated and horizontal wells planned to drill through the interval extended from top Sadi to the end of Zubair formation.
- 7- Increasing the well inclination to more than 30° causes to narrow the mud weight window and increases the required mud weight to sustain the more complicated shear failure.

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