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A Comprehensive Geomechanical Study to Understand Drilling Challenges in the Eridu Oil Field, Southern of Iraq

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Abstract

In recent years, the Eridu oil field has emerged as a key player in the petroleum industry in southern Iraq as it is the biggest Iraqi oil discovery in 20 years. Extending along a vast area of 5806 km^2, the field has commercial oil reserves in formations such as Mishrif, Nahr Umr, Zubair, and Yamama. However, drilling operations in this field have faced significant challenges, including delays and suspensions caused by wellbore instability. One of the main obstacles encountered during drilling operations in the Eridu oil field is the occurrence of partial losses in weak vugs dolomite formations, as well as issues related to sever borehole instabilities such as drilling in tight holes, caving, and breakout due to shear failure in the borehole wall. To address these challenges, a 1 D Geomechanical model (1-D MEM) was constructed using data from vertical wells to better understand the underlying causes of drilling problems. The findings of the 1-D MEM, particularly in relation to mechanical rock properties, rock Elasticity factors, pore pressure, and fracture gradient complex formations like Tanuma and Mishrif, were instrumented in planning drilling operations for inclined and highly deviated wells. By utilizing open hole well logging data and calibrating the model with various resources of data including drilling observations, core mechanical analyses, and pore pressure measurements, a more accurate assessment of wellbore instabilities was achieved. The analysis revealed that many of the wellbore instabilities, such as pack-off, breakout, and stuck pipe, were attributed to the insufficient mud weight that failed to support the rock in the borehole wall. To avoid these issues, it was determined that a safe mud weight range of 11-12.5 ppg is necessary to prevent wellbore instability in shale formations. The study also highlighted the importance of using proper mud weight to prevent shear failure and other drilling complications. The findings of this study provide insights that can be utilized as a cost-effective tool for planning directional and horizontal drilling operations in the Eridu oil field. The accuracy of the failure criteria and geomechanical model is significantly superior and aligns with the analysis of breakouts observed in the caliper and image logs.

Keywords: Geomechanical Study; Drilling Challenges; 1-D Geomechanical Model; Wellbore Instability Eridu oil field.

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1- Introduction

Wellbore instability occurs due to chemical reactions between the formation and the drilling fluids, as well as an imbalance between the wellbore pressure applied and the fluid pressure in the formation. [1]. The problems with the instability of the wellbore during drilling operations, an appropriate well design needs to be made for the formations that will be drilled and maintained for production, this means that the in-situ stress state, pore pressure, and Geomechanical properties of the reservoir formation need to be understood [2]. The shale formations such as the Tannuma, Ahmadi, Khasib, and portions of Zubair and Mishrif formations account for approximately 70% of the downhole issues encountered when drilling to the targeted pay zones [3]. Chemically, mud weight influences instability. To ensure stability, the mud weight must be maintained within a certain range. It should be greater than the pore pressure gradient value to prevent breakout failure, and it must be less than the formation fracture gradient to prevent the issue of mud loss into the formation and eventual tensile failure of the formation. High mud weight can reactivate natural open fractures by intruding drilling fluid into them, producing major drilling issues. However, sediment-formation chemical interactions may make shale zones unstable [4]. Horizontal and highly deviated wells under normal fault stress regimes are more problematic than low-inclined wells due to wellbore compressive or shear failure. As the wellbore stress difference approaches its maximum with inclination, wellbore stability difficulties become more obvious, therefore accurate good trajectory and mud weight design are critical to avoid equipment downtime, NPT, and expensive complexity [5].

- Area of study

Eridu oil field was discovered in Mishrif B formation after drilling the first exploration well Eridu-1 (3168 m MD, 3150 m TVDSS). Many drilling problems were encountered while drilling Eridu-1 and the operation

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deviated from the planned program as shown in (Fig. 1). The Eridu oil field within the area in the South-West part of the Republic of Iraq, on the boundary between the Thi-Qar and Muthanna Provinces, at 120 km to the West from Basra, 150 km to the West from the West Qurna-2 oilfield as shown in (Fig. 2). The total field area is 5665 square kilometers (before expansion). In accordance with the approval of the Ministry of oil (MoO) regarding expansion of the Block 10 Contract Area for 141 sq. km, the new area of Block 10 is 5806 sq. km [6].

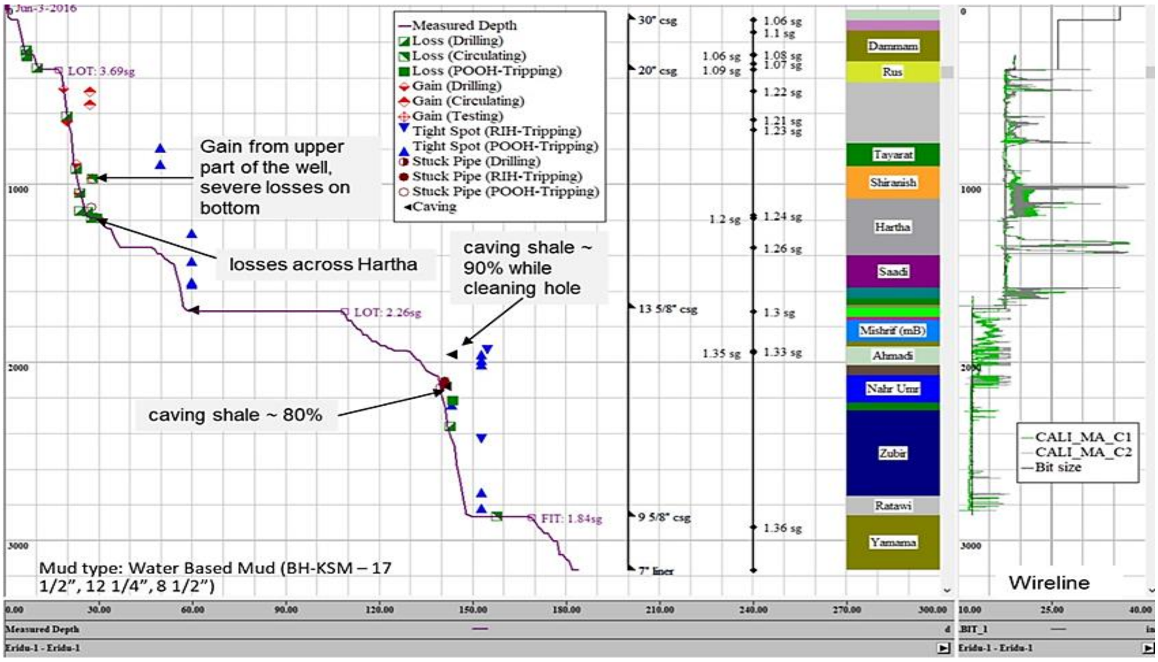

Fig. 1. Example from Drilling Operation Problems in Exploration Well ER-1 [6]

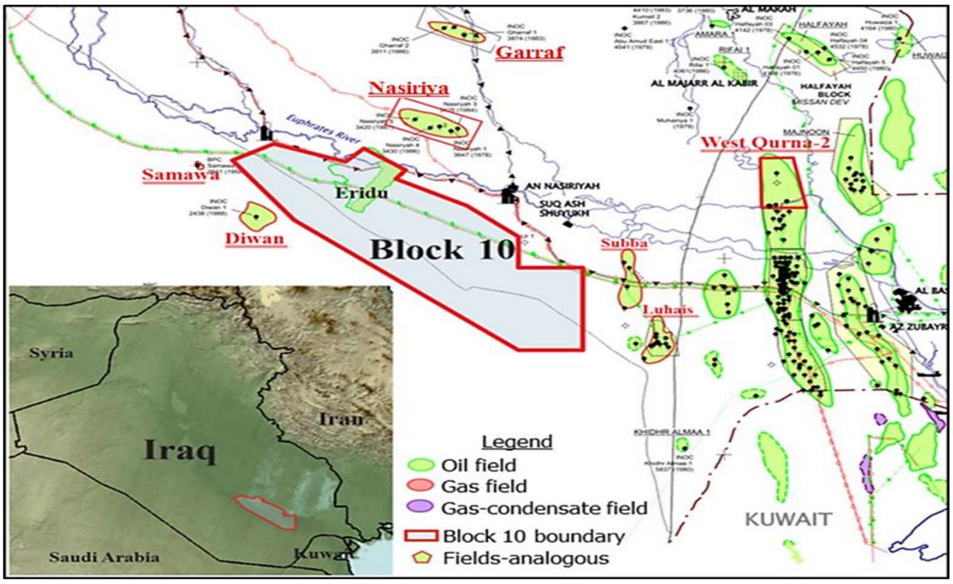

Fig. 2. Block 10 (Eridu oil field) Location Map [6]

2- Methodology

Perform simulation studies including:

1- In-situ stresses;
2- Rock strength;
3- Formation pore pressure (PP) prédiction.
4- Borehole stability prediction.
5- Recommendations for well trajectory planning, and critical angles (inclination and azimuth) of penetrating the unstable zones.
6- Recommendations for mud weight.

3- Geomechanical Workflow

Geomechanics is the study of the relationship between geology and the mechanical properties of rocks. In other words, it focuses on the effects of stress on the deformation or failure of rocks as a result of changes in stress direction, anomalous pressure, temperature, and fluid flow resulting from production [7]. To understand the reason behind the borehole problems such as (losses, breakout, and stuck) a 1 D Geomechanical model was conducted to mitigate borehole instability by estimating the Safe mud weight window used to drill 12 ¼'' and 8 ½ '' hole sections as shown in Fig. 3.

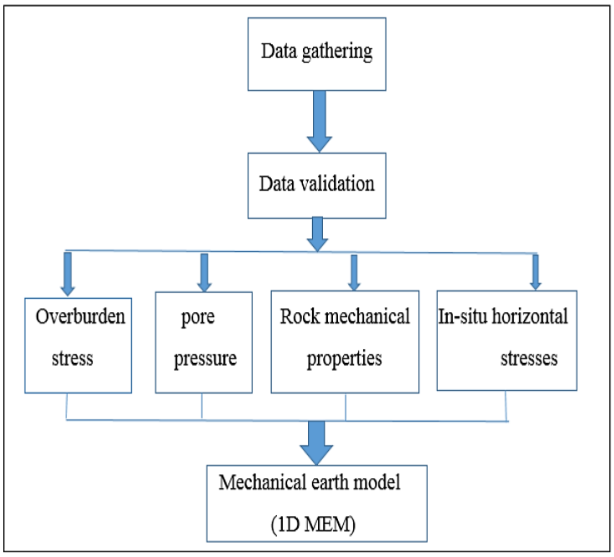

Fig. 3. Geomechanical Work Flow

3.1. Collecting data

The necessary data used to build a basic 1D-MEM.including gamma ray, density, sonic logs (compression and shear slowness), Image log (FMI), caliper, mud logs (master logs), formation pressure measurements, and laboratory measurements [8]. The data set was acquired and retained from six vertical w ells in order to predict wellbore problems particularly, Ca ving shales in the Tanuma Formation and breakout pheno mena in the Mishrif Formation. To build a 1-D geomechanical Model open hole logs measurements, core analysis data, and drilling observation data should be utilized in software [9]. To investigate wellbore instability, the Mogi Coulomb and Stassi d' Alia failure criteria were applied.

3.2. Vertical Stress

Is the pressure exerted on a point by the weight of fluid-bearing formations above it [9]. It is one of the major parameters of each analysis of the Geomechanical model. In the current study, the vertical stress is calculated by using the extrapolation method to fill the air gaps between bulk density logs in the computing process of overburden stress. Density is extrapolated up to the mud line by applying the following geometric fit (Eq. 1) [11], by applying this equation, the density of the unlogged interval is estimated as shown in Fig. 4.

$$\rho\ extapolated = \rho\ mudline + Ao \times (TVD - \text{Air gap}) \quad (1)$$

Where: $\rho\ mudline$ is the density at the ground level (The density of the soil is 1.85 gm/cc). Air Gap represents the distance between the ground level and the rig floor (m). TVD is the true vertical depth (m). A_o and α are fitting parameters.

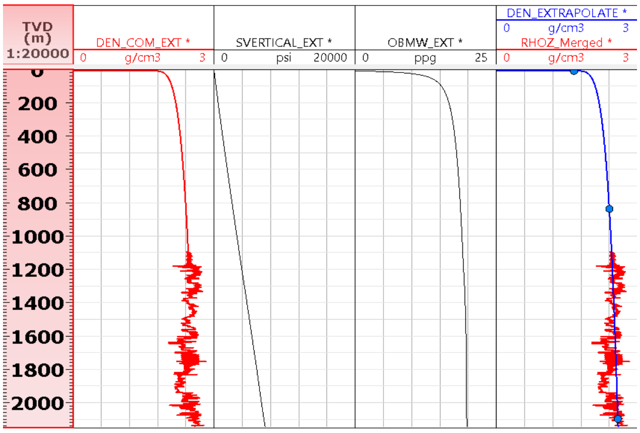

Fig. 4. Vertical Stress that Estimated by Extrapolated Method in ER 2

3.3. Pore pressure

Pore pressure is a very important mechanical parameter that is used for determining the horizontal principal stresses in the ground and to predict a safe mud-weight window for drilling a stable wellbore. [12]. Abnormal formation pressure is the difference between subsurface fluid interstitial and pore pressure. The hydrostatic pressure has a direct proportionate relationship with the total height of a water column that stretches from the ground up to the attention formation. Because of this, the pore pressure tends to vary quite a little from one location to another. Nevertheless, the standard computed value is widely considered to be 0.433 times the depth in psi for fresh water and 0.465 times the depth in psi for salty water [13]. Resistivity and sonic logs could be utilized to derive the pressure directions and estimate the pressure of the pores in shale. The pore pressure estimation and calculations must be executed continuously [14]. In the current study, the Eaton slowness method was used to estimate pore pressure. Eaton calculation provided reasonable results by utilizing concerned data (open hole logs, core analysis data, drilling and mud report observations) the validity of the Eaton model has been checked by the real pressure measurement which is Modular Formation Dynamics Tester (MDT), and these pressure point match with Easton calculation by using Techlog 2021 software (Fig. 5). Eq. 2 was used to estimate pore pressure.

$$P_P = OBG - (OBG - P_{pn}).(\frac{\Delta t_n}{\Delta t_o})^x \quad (2)$$

Where (Δt_n) is the transit time of sonic wave in shales at the normal pressure (Δt_o) is the transit time of sonic in shales which comes from the well logging. x: dependent on the normal compaction trend line, OBG, overburden gradient, P_{pn}: is the gradient of normal hydrostatic pore pressure.

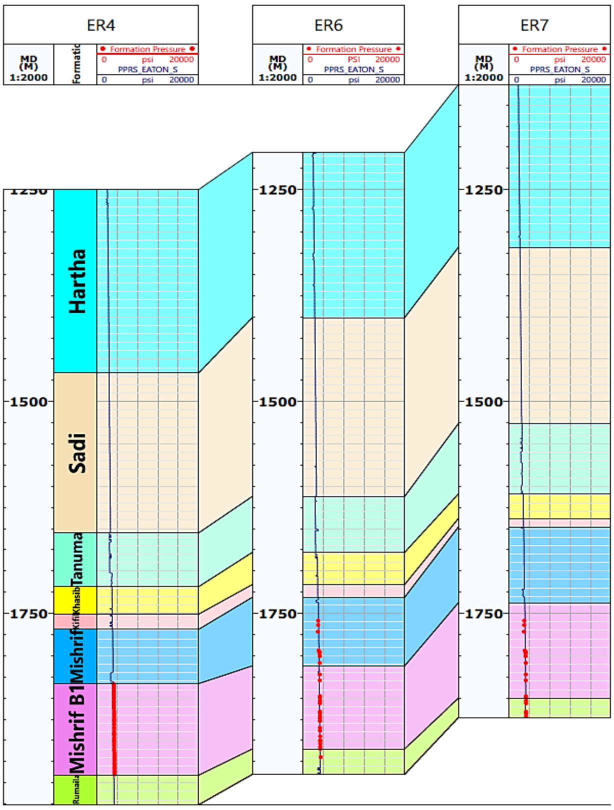

Fig. 5. Pore Pressure Estimated by Eaton-Slowness Method in ER4, ER6 and ER7

3.4. Elastic properties

Both the density log and sonic logs (P wave and S wave delay) are frequently used to estimate the elastic parameters of the rock [15]. However, the parameters are three to four times larger than their actual values and must be converted to their static values using rock type and geological context correlations. A Generic - John Fuller Correlation which gave best matching when calibrated with core measurement data (Triaxle test results).

3.5. Rock Strength

Rock mechanical properties directly impact the stability of the wellbore; in general, there are two methods utilized to determine rock mechanical properties, direct laboratory measurement and indirect interpretation of well logging data [16]. Using proper laboratory techniques increases the direct method's precision but is costly and time-consuming. In addition, obtaining a comprehensive profile of formation strength is difficult without conducting numerous experiments. The indirect method uses acoustic log data and log strength correlations to predict rock strength. This method requires precision experimental data to establish correlations between force and velocity [17]. The strength parameters: unconfined compressive strength UCS, Friction angle FANG, as well as cohesive strength, are considered the most important rock properties that are used in wellbore stability and drilling workflows. These parameters were computed from compressional caustic which provide the best matching with core laboratory test results. Plumb Generic Static Young's Modulus Correlation (YME_STA) method was used to compute (UCS), the mud weight window and wellbore stability are determined by unconfined compressive strength (UCS), also, it is critical for reservoir subsidence and acidification studies [18]. Fig. 6 depicts the rock strength parameters derived from the (Tech-log software program 2021), with the result demonstrating how the software output matched with core analysis laboratory tests that are shown in distributed points. Friction angle was calculated from GR. with a linear correlation, this approach maps Gamma Ray to Friction Angle. To the friction angle, a cutoff is applied. GR 40 g API is mapped to FANG 35 deg. with default parameters and GR 120 g API is mapped to FANG 20 deg. The computed FANG is forced to 15 degrees if it is less than that. If FANG is more than 40 degrees, it must be 40 degrees. [11] see Fig. 7.

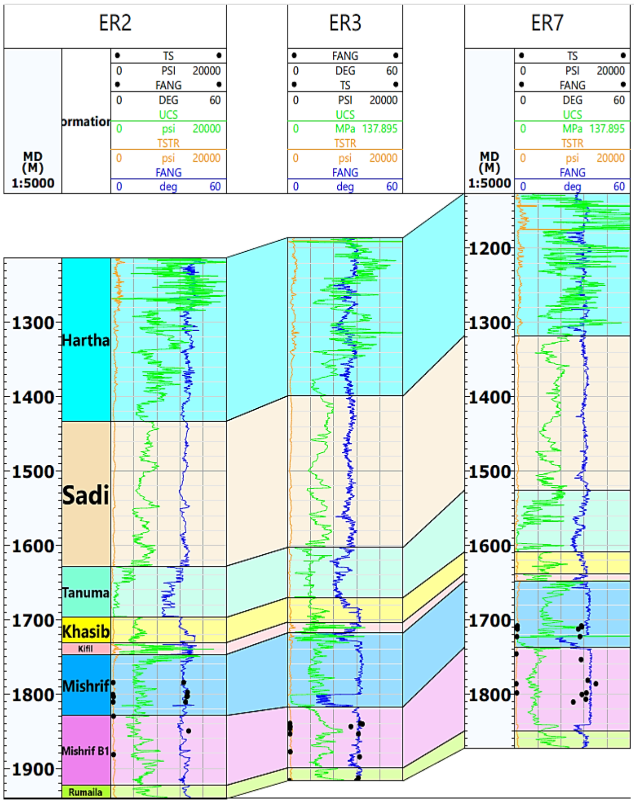

Fig. 6. Example of Elastic Properties and Rock Strength Parameters from Eridu Oil Field

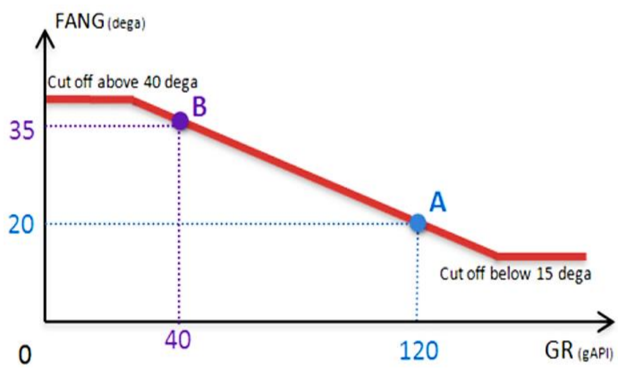

Fig. 7. FANG Estimated from GR

3.6. Magnitude of Horizontal stress (Maximum and minimum)

The maximum horizontal stress is considered the most challenging parameter in the Geomechanical model because it is related to the rock failure with a significant amount of uncertainty, the minimum horizontal stress is determined by the leak-off test [12]. The magnitude of horizontal stresses was calculated depending on measurements of vertical stress, pore pressure, mechanical properties, strain, etc. Poro-elastic horizontal strain model was applied to calculate the magnitudes of horizontal principal stresses using eqs. 3 and 4 below:

$$\sigma_H = \frac{v}{1-v}\sigma v + \frac{1-2v}{1-v}\alpha Pp + \frac{E}{1-v^2}\varepsilon_h + \frac{vE}{1-v^2}\varepsilon_H \quad (3)$$

$$\sigma_h = \frac{v}{1-v}\sigma v + \frac{1-2v}{1-v}\alpha Pp + \frac{E}{1-v^2}\varepsilon_H + \frac{vE}{1-v^2}\varepsilon_h \quad (4)$$

Where: v is Poisson's ratio, E is Young's Modulus, α is Biot coefficient, ε_h is the minimum horizontal strain, and ε_H is the maximum horizontal strain. Fig. 5 shows the estimation of pore pressure, Elastic properties, and In-situ stress for Eridu A. The result was calibrated with a core laboratory test. Various fault regimes were shown for intervals of interest as a result of the huge tectonic movements that Iraq was subjected to. In other words, in the South of Iraq stratigraphic column of the Upper/Late Cretaceous period witnessed a geodynamic inversion from the extensional to compressional tectonics movements [19]. The elastic rock properties and rock mechanical strength values proposed for wells in the Eridu oil field are presented in Table 1.

Table 1. Average Elastic Rock Properties and Rock Mechanical Strength Values

Formation	Young modulus YME (Mpsi)	Poison Ration Pr %	unconfined compressive strength UCS (psi)	Tensile strength (psi)	Friction angle (degree)
Hartha	1.8-2.5	0.19-0.25	7515- 9641.	750-968	31-33
Sadi	1.4-1.6	0.21-0.24	5581.9 -6274.2	560-627	34-36
Tanuma	1.09-1.7	0.22-0.28	4496.5-5807	449-580	29.09-36.73
Khasib	1.02-1.6	0.2-0.25	4343.5-6358.6	434-536	34.5-38.8
Kifil	1.23-2.4	0.26-0.3	4094.4-5528.8	420-550	32-37
Mishrif A	1.23-2.4	0.24-0.3	5201- 6151	520-615	35-38
Mishrif B	1.1-2.3	0.2-0.28	3615.4 -5783	361-578	33-37
Rumaila	1.1-2	0.22-0.24	5927 -6586	592-658	26-32
Ahmadi	0.9-1.6	0.2-0.31	4500-5898	505-625	26-29

4- Wellbore Failure and Prevention

When a borehole is drilled into the rock, stresses are redistributed. A yield zone may form around a borehole if the stresses exceed the yield criterion. The wellbore instability study includes shear and tensile failure identification modeling. Various failure criteria, including (Mohr-Coulomb, Mogi-Coulomb, and Stassi d' Alia failure criteria), were used to predict the shear failure around the well bore. In the current study, the criteria that are used to determine the failure around the wellbore were (Mogi Coulomb and Stassi d' Alia failure criteria). The results shown in Fig. 8 to Fig. 10, indicate that the two methods are a good match with caliper logs, but the results from the Mogi–coulomb criterion method showed the best agreement with breakout observed in caliper log Fig. 9, whereas the results from the Stassi d' Alia failure criteria method show overestimated failure from what is actually present Fig. 10, so the Mogi-coulomb criteria is selected to predict the failure for Eridu oil field. Mogi failure criteria consider the effect of the intermediate stress component in the failure analysis, which is the best indication for predicting the failures around the wellbore during drilling [20]. Eq. 5 represents the Mogi-coulomb parameters whereas (Eq. 6) shows the Stassi d' Alia failure:

$$\tau oct = a + b\,\sigma m,2 \quad (5)$$

Where: $\tau oct = \frac{1}{3}\sqrt{(\sigma 1 - \sigma 2)^2 + (\sigma 2 - \sigma 3)^2 + (\sigma 3 - \sigma 1)^2}$, $\sigma m,2 = \frac{\sigma 1+\sigma 2}{2}$, $a = \frac{2\sqrt{2}}{3}\cos(\emptyset)$, $b = \frac{2\sqrt{2}}{3}\sin(\emptyset)$.

Where: τoct: octahedral shear, C: cohesion strength (psi) and the $\emptyset$ is the internal friction angle (degree), stress; a & b: strength parameter; σm,2: mean effective stress.

Stassi

$$[(\sigma_1-\sigma_3)^2 + (\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2] = 2(UCS - T_O)(\sigma_1+\sigma_2+\sigma_3) + 2T_O UCS \quad (6)$$

Where: σ_1: Maximum Principal Stress (psi), σ_3: Minimum Principal Stress (psi), σ_2: Intermediate Principal Stress (psi), UCS is the Unconfined Compressive Strength (psi), and T_0 is the tensile strength.

4.1. Sensitivity analysis for the most problematic formation in the Eridu oil field

Analysis of mud weight sensitivity to wellbore orientation establishes the relationship between required mud weights and wellbore inclination and azimuth at a given depth [21]. Stereonet diagrams demonstrate that the wells are more stable with deviation ranging between (0-30 °). On the other hand, potential breakdown failure occurs at an inclination greater than 50 degrees toward the max. horizontal stress orientation. Even if the weight of the mud is low, the resulting stereonet plots demonstrate that the inclination between 0 and 40 degrees is the most stable concerning the shear failure. Even with a high mud weight, shear failure can happen for inclines between 40 and 90 degrees in both the direction of the minimum horizontal stress and the direction of the maximum horizontal stress, as shown in Fig. 11 to Fig. 16 in (Tanuma, Mishrif, and Ahmadi formation) the lithology of these formations contains shale and shear failure observed. Also, the plot showed no effect on the Azimuth on the mud weight. The results indicate that the safe mud weight window of shear failure (breakout) narrows in wells with an inclination greater than 35 degrees. Based on this analysis of the Eridu oil field, the wellbore trajectory should be designed to avoid a high deviation, or the mud weights should be sufficient to prevent collapse failure and tolerable limited mud loss.

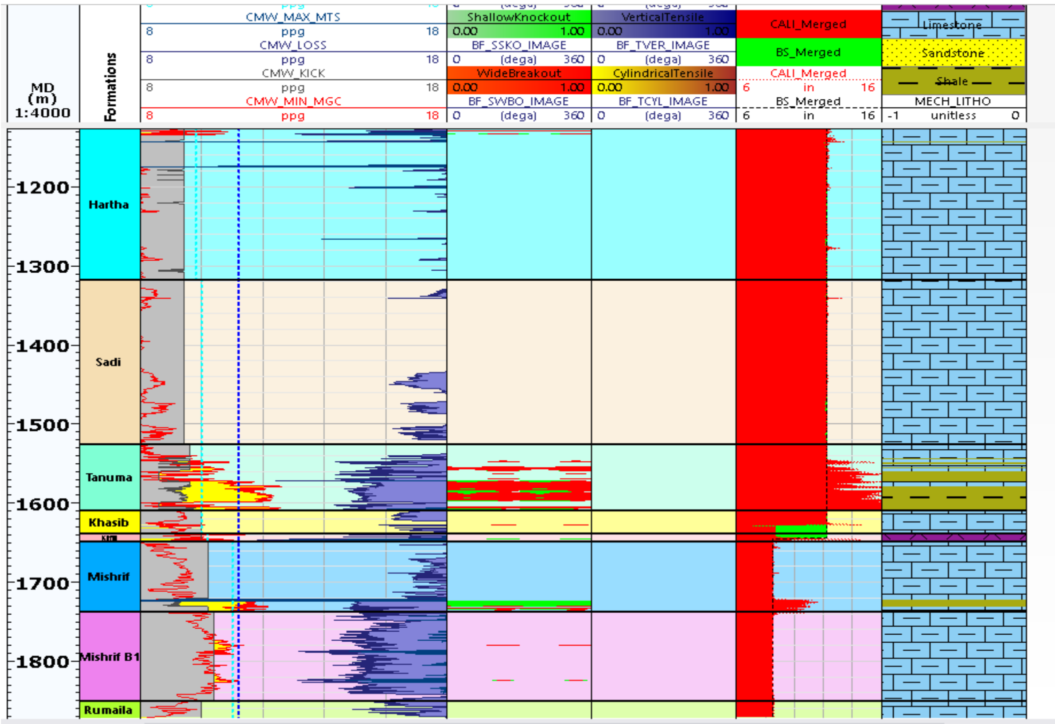

Fig. 8. Wellbore Instability of ER- 7 by Mogi-Coulomb Criteria

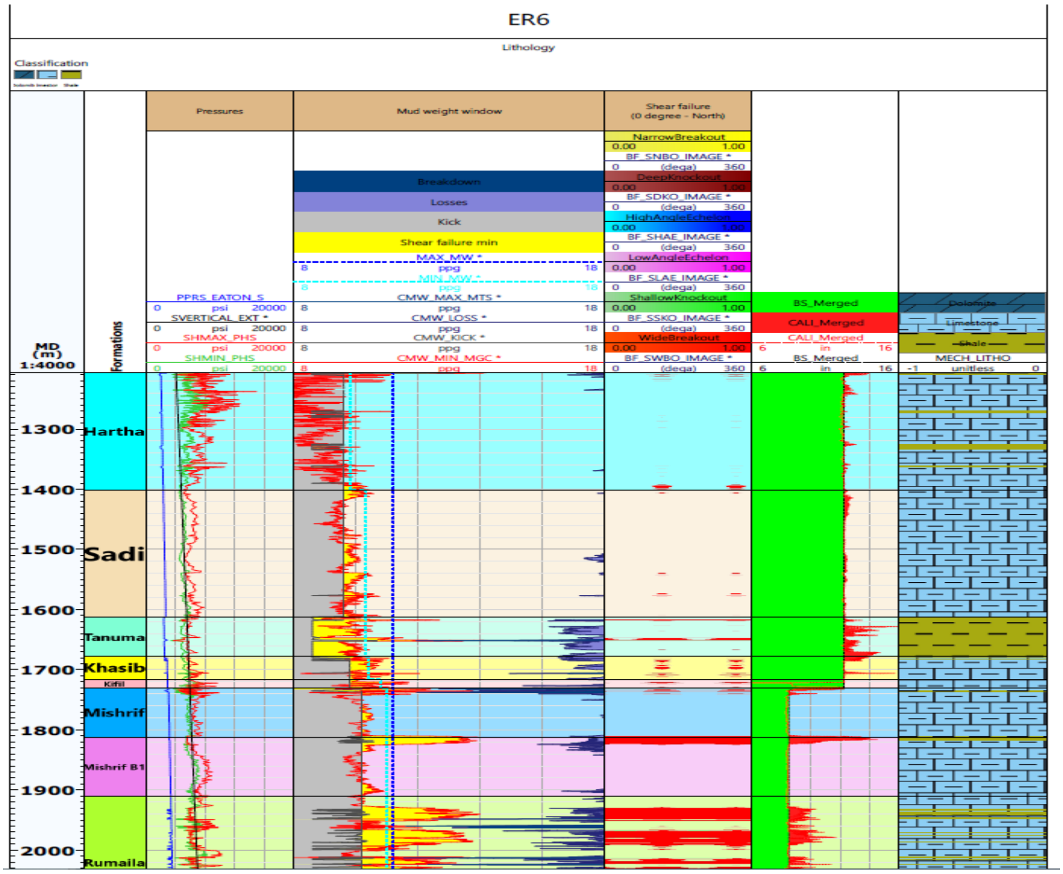

Fig. 9. Wellbore Instability of ER-6 by Mogi-Coulomb Criteria

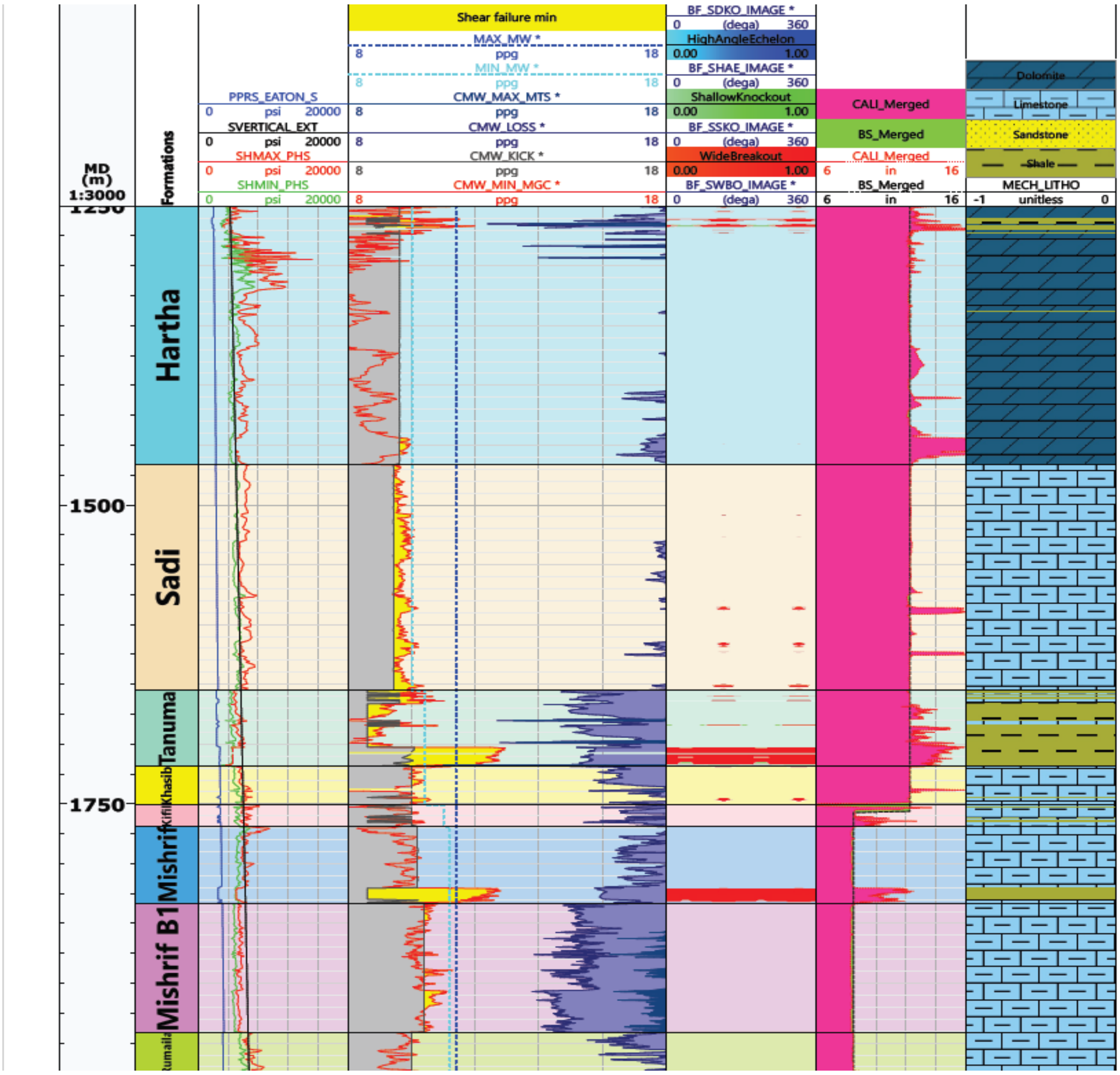

Fig. 10. Wellbore Instability of ER- 4 by Stassi d' Alia Failure Criteria

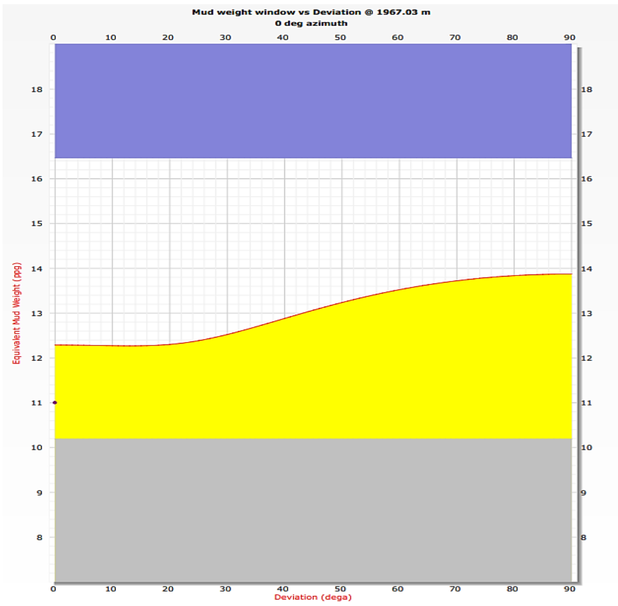

Fig. 11. Mud Weight Window Vs Inclination in Ahmadi Formation

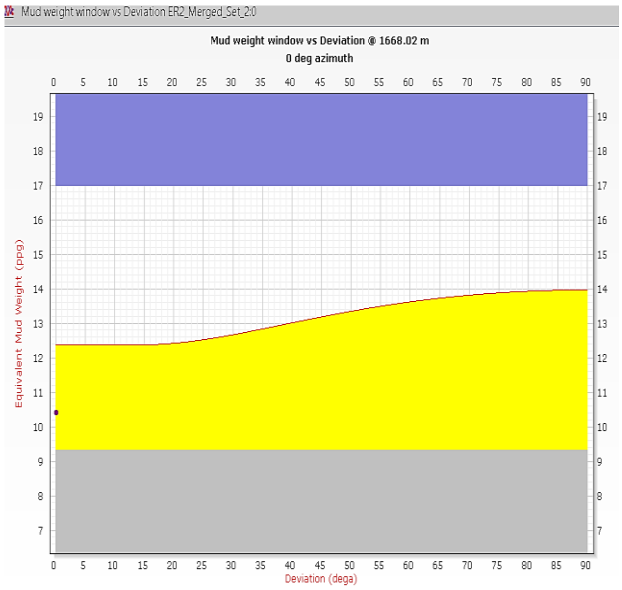

Fig. 12. Mud Weight Window Vs Inclination of Tanuma Formation

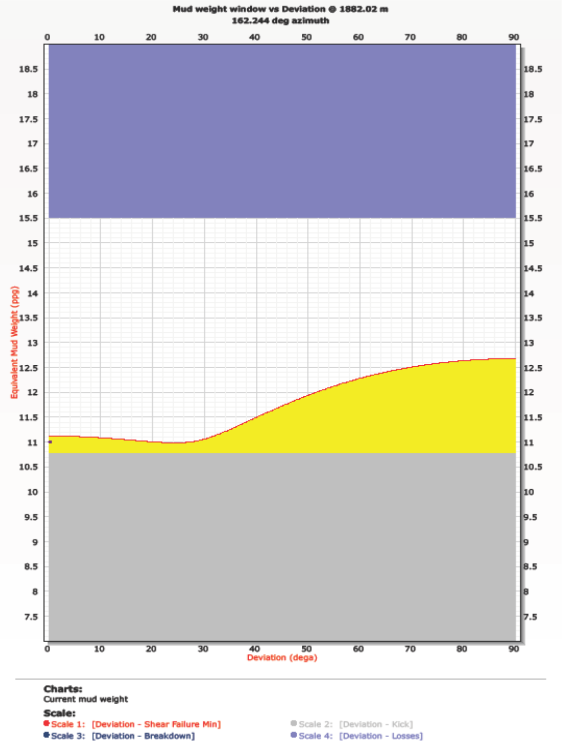

Fig. 13. Mud Weight Window Vs Inclination in Lower Interval of Mishrif Formation

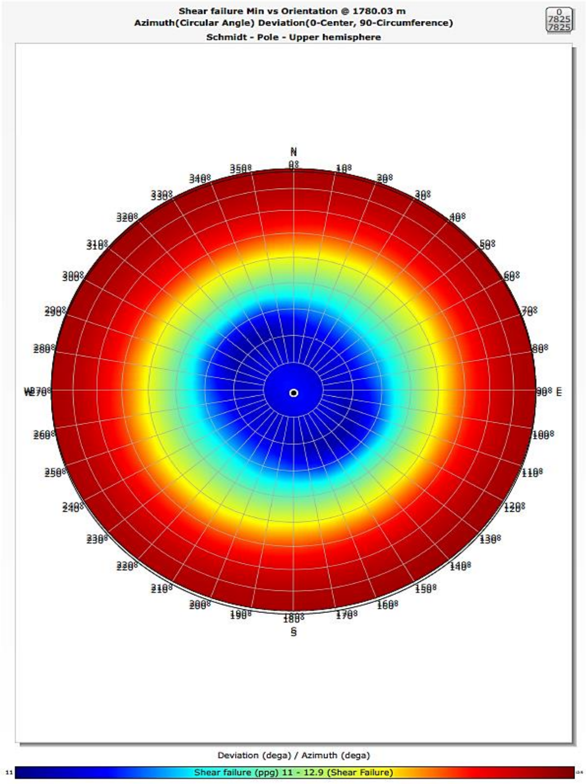

Fig. 15. Shear Failure Vs Inclination in Mishrif Formation

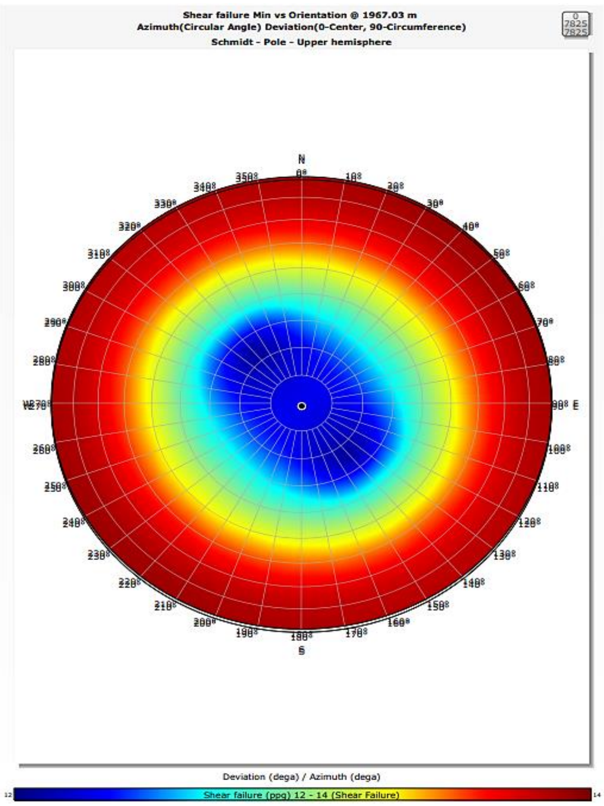

Fig. 14. Shear Failure Vs Inclination in Ahmadi Formation

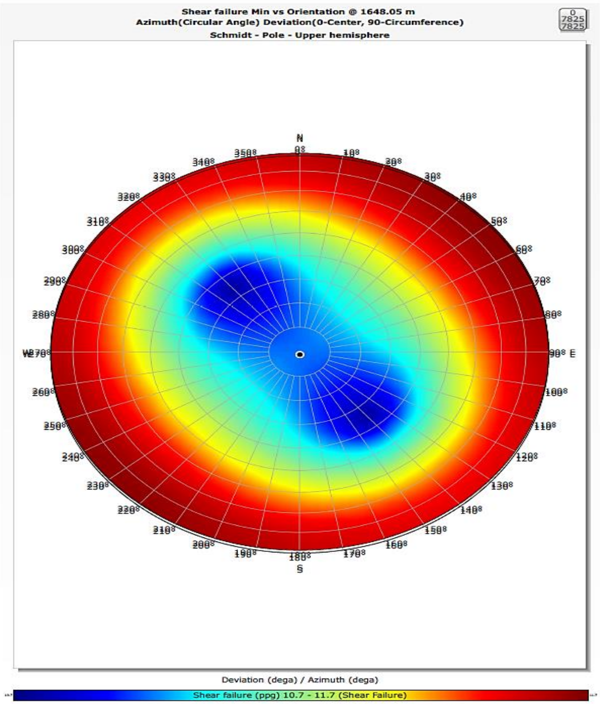

Fig. 16. Shear Failure vs inclination in Tanuma Formation

5- Conclusions

The main problem identified in the Eridu oil field is shear failure rather than tensile fracturing of the formation, leading to significant losses. A single depth sensitivity analysis has revealed that the minimum horizontal stress orientation is at 140 degrees from the north, while the maximum horizontal stress orientation is at 50 degrees from the north. This indicates that shear failure is the predominant factor, with no evidence of formation tensile failure. To mitigate wellbore instability problems, it is recommended to maintain a mud weight range of 11-12.5 ppg. According to the results of the depth sensitivity analysis and fault regime in the Eridu oil field, the most effective approach for drilling deviated and horizontal wells is towards the minimum horizontal stress direction, which is at an angle of 140 degrees from north. The fault regime in the Eridu oil field is divided into two regions: strike-slip fault regimes in carbonate rocks and normal fault regimes in clastic rocks. It was observed that the mud weight window narrows in the Tanuma, Ahmadi, and Mishrif formations when the inclination exceeds 30 degrees. Additionally, there was a lack of sufficient mud weight used in drilling vertical wells, specifically in the Tanuma, Mishrif, and Ahmadi formations. It is recommended to use a mud weight of 11.5 ppg in the Ahmadi formation, 12.5 ppg in the Lower section of the Mishrif formation, and the Tanuma formation to address these issues effectively.

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دراسة جيوميكانيكية شاملة لفهم الاسباب التي تؤدي الى مشاكل الحفر وايجاد الحلول لها في حقل اريدو النفطي (جنوب العراق)

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الخلاصة

في السنوات الأخيرة، برز حقل أريدو النفطي باعتباره محورًا رئيسيًا في صناعة النفط في جنوب العراق حيث يعد أكبر اكتشاف نفطي عراقي منذ ٢٠ عامًا. بالإضافة إلى مساحتها الشاسعة البالغة ٥٨٠٦ كم^{2} واحتياطياتها النفطية التجارية في تكوينات مثل مشرف ونهر عمر والزبير واليمامة ومع ذلك، واجهت عمليات الحفر في هذا الحقل تحديات كبيرة، بما في ذلك التأخير والتعليق الناجم عن عدم استقرار البئر. إحدى العوائق الرئيسية التي تمت مواجهتها أثناء عمليات الحفر في حقل نفط أريدو هي حدوث خسائر جزئية في تكوينات الدولوميت ذات الفجوات الضعيفة، بالإضافة إلى المشكلات المتعلقة بعدم الاستقرار الشديد في الآبار مثل الحفر في الثقوب الضيقة، والكهوف، والاختراق بسبب فشل القص في جدار البئر. ولمواجهة هذه التحديات، تم إنشاء نموذج جيوميكانيكي ثلاثي الأبعاد (١-D MEM) باستخدام بيانات من الآبار العمودية لفهم الأسباب الكامنة وراء مشاكل الحفر بشكل أفضل. وقد تم استخدام نتائج MEM أحادية الأبعاد، خاصة فيما يتعلق بخصائص الصخور الميكانيكية، وعوامل مرونة الصخور، وضغط المسام، والتكوينات المعقدة المتدرجة للكسر مثل تنومة ومشرف، في تخطيط عمليات الحفر للآبار المائلة والمائلة بشدة. ومن خلال استخدام بيانات تسجيل الآبار المفتوحة ومعايرة النموذج بموارد مختلفة من البيانات بما في ذلك ملاحظات الحفر والتحليلات الميكانيكية الأساسية وقياسات ضغط المسام، تم تحقيق تقييم أكثر دقة لعدم استقرار البئر. وكشف التحليل أن العديد من حالات عدم الاستقرار في البئر، مثل التعبئة والكسر والأنابيب العالقة، تعزى إلى الوزن غير الكافي من الطين الذي فشل في دعم الصخور في جدار البئر. لتجنب هذه المشكلات، تقرر أن نطاق وزن الطين الآمن الذي يتراوح بين ١١-١٢,٥ ppg ضروري لمنع عدم استقرار البئر في التكوينات الصخرية. كما أبرزت الدراسة أهمية استخدام الوزن الطيني المناسب لمنع فشل القص ومضاعفات الحفر الأخرى. توفر نتائج هذه الدراسة رؤى يمكن استخدامها كأداة فعالة من حيث التكلفة لتخطيط عمليات الحفر الاتجاهي والأفقي في حقل نفط أريدو. دقة معايير الفشل والنموذج الجيوميكانيكي متفوقة بشكل كبير وتتوافق مع تحليل الاختراقات التي لوحظت في سجلات تخطيط الابار.

الكلمات الدالة: دراسة جيوميكانيكية، مشاكل الحفر، نموذج الجيوميكانيكي أحادي الأبعاد، عدم استقرار حفرة البئر، حقل أريدو النفطي.