Available online at http://ijcpe.uobaghdad.edu.iq and www.iasj.net
Iraqi Journal of Chemical and Petroleum Engineering
Vol. 24 No.3 (September 2023) 33 – 43
EISSN: 2618-0707, PISSN: 1997-4884

2D and 3D Modeling of Rock Mechanical Properties of Khasib Formation in East Baghdad Oil Field

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Abstract

Knowing the distribution of the mechanical rock properties and the far field stresses for the field of interest is an important task for many applications concerning reservoir geomechanics, including wellbore instability analysis, hydraulic fracturing, sand production, reservoir compaction, and subsidence. A major challenge with determining the rock's mechanical properties is that they cannot be directly measured at the borehole. Furthermore, the recovered carbonate core samples for performing measurements are limited and they provide discrete data for specific depths.

The purpose of this study is to build 2D and 3D geomechanical models of the Khasib reservoir in the East Baghdad oil field/ Central area. TECHLOG.2015.3 software was used to build the 1D-MEM while Petrel E&P 2018.2 software was used to build the 3D distributions of rock mechanical properties. The Khasib formation has nine units (from K1 to K9). The current results support the evidence that the horizontal stresses are somewhat similar for all layers in the vertical case, but their distribution varies horizontally due to the changes in pore pressures. The pore pressure increases vertically, but its distribution within one layer is different due to the production from different wells. Elastic and strength characteristics of rock, including Young modulus, Poisson ratio, and unconfined compressive strength (UCS), have the same behavior, the highest value of the parameters appeared in the surface layer (K1). This layer is more stiff than other layers that have high porosities and high permeability. The internal friction angle for all formations ranges between 38^o-40^o, which gives a good harmonization with the limestone friction angle. The 3D distribution of the rock's mechanical properties revealed the carbonate heterogeneity because of its marine depositional environment and complex diagenetic processes. The findings of this study can be used for future geomechanical applications in the East Baghdad oil field including wellbore stability analysis, fault reactivation, and CO_2 sequestration.

Keywords: 3D MEM, 1D mechanical earth model, Khasib reservoir, East Baghdad Oil field, Mechanical rock properties.

Received on 02/10/2022, Received in Revised Form on 25/02/2023, Accepted on 26/02/2023, Published on 30/09/2023

https://doi.org/10.31699/IJCPE.2023.3.4

1- Introduction

Carbonate reservoirs, by nature, have unique depositional environments and complex diagenetic processes that control the spatial distributions of their mechanical properties. The result is that brittle, ductile, fractured rocks, vugular pores, or tight formations may all exit within small intervals of these reservoirs [1, 2]. Typically, coring and rock testing are the ideal methods to determine the rock's mechanical properties, but core samples can be only samples at a well location, as well as core samples, are normally limited due to cost and time-saving purposes [3, 4]. To overcome these challenges, dynamic determination of rock mechanical properties can be considered as the starting point to quantify these properties for applications related to reservoir geomechanics.

Comprehensive knowledge of the state of stress and its changes over time plays an important role in the economic and security situation of hydrocarbon reservoirs, both before and after production. Changing ground pressures affect various aspects such as well stability, fault reactivation, and rock integrity [5]. Before starting the drilling operations, the stresses are in balance, but it will be different after drilling the rock and extracting the hole. This will result in a gap or a change in the stress magnitudes. This should be balanced or replaced by the drilling mud. This means that the pressure of the mud column spreads causing pressure around the wellbore, trying to restore the balance to the wellbore and prevent the rock from failing by regulating the stresses around the wellbore [6]. The estimate of rock properties is very important in predicting rock failure. Rock failure during drilling is an important problem to be solved in petroleum technology [7].

The properties of the rocks are not uniform, as they vary horizontally and vertically according to the type of rocks, rock formation, type of faults, and the causes of the tectonic system. Therefore, it is necessary to evaluate rock deformation as a response to the drilling operations, completion, and production processes.

Building a three-dimensional geomechanical model is

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very useful to show the distribution of mechanical properties of rocks including rock strength, elastic properties, as well as stress distribution, and knowing of pore pressure magnitudes at different depths. The purpose of the study is to create two and three-dimensional geomechanical models of the Khasib formation in the East Baghdad Oil Field to be useful for future applications related to reservoir geomechanics.

2- Area of Study

East Baghdad oil field is located in the center of Iraq, about 10 km east of Baghdad city as shown in Fig. 1. The production section of the East Baghdad oil field primarily consists of carbonate rocks (Tanuma, Khasib, and Zubair reservoirs). Khasib formation horizon contains nearly half of the EB field’s OOIP [8]. It is an upper Cretaceous formation, about 100 m thick found at depths ranging from (2100 to 2300) m. Chalky mudstone with frequently abundant micro fissures is the main rock type of the Khasib formation. Al-Khasib formation is divided based on the GR Log and Resistivity log into nine layers (K1-K9), the main reservoirs (oil bearing) are the K2, K3, K4, K5, and K6, and the other layers contain oil, but in very small quantities [8].

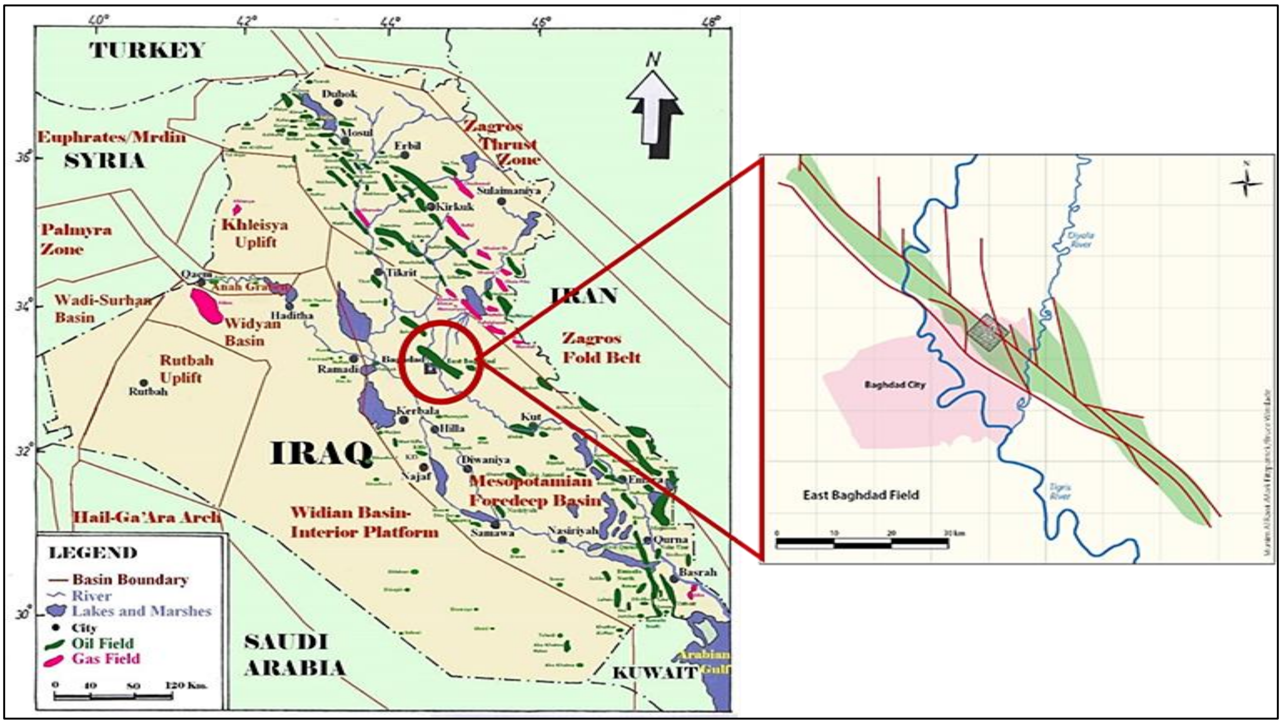


Fig. 1. Location Map of East Baghdad Oil Field (GEO ExPro, 2016)

3- Materials and Methods

3.1. 1D MEM

A 1D MEM has been constructed from well logs by using Techlog software. The data used for building 1D MEM are bulk density, gamma ray, sonic logs, as well as the final well reports and other related data.

The vertical or overburden stress refers to the overlaying rocks with formation thickness by integrating the weight of these rocks [9]. This stress can be calculated using Eq. 1.

$$\sigma_v = \int_0^H \rho_b H g dH \quad (1)$$

The dynamic elastic properties have been also calculated based on sonic and bulk density logs. Eqs. 2 through 5 have been used to determine the dynamic Young's modulus, Poisson ratio, bulk modulus, and shear modulus, respectively. With respect to the static elastic properties, it has been estimated using the correlations in the software. Eq. 6 was used to determine the static Poisson’s ratio, while the static Young’s modulus was calculated based on the John Fuller correlation [10].

$$E_{dyn} = \frac{9 * G_{dyn} K_{dyn}}{G_{dyn} + 3K_{dyn}} \quad (2)$$

$$v_{dyn} = \frac{3K_{dyn} - 2G_{dyn}}{6K_{dyn} + 2G_{dyn}} \quad (3)$$

$$K_{dyn} = 13474.45 * \left[\frac{\rho_b}{(\Delta t_{shear})^2}\right] - \frac{3}{4} * G_{dyn} \quad (4)$$

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

$$v_{sta} = v_{dyn} * PRmult \quad (6)$$

Where: σ_v vertical stress, psi, ρ_b bulk density, g/cc, H total depth, m, Δt_{shear} sonic shear velocity, μs/ft, E_{dyn} dynamic young modulus, Mpsi, G_{dyn} dynamic shear modulus, Mpsi, K_{dyn} dynamic bulk modulus, Mpsi, υ_{dyn}: Dynamic Poisson’s ratio, unitless, υ_{sta}: Static Poisson’s ratio, the PR $_{multiplier}$ factor of the Eq. 6 can be adjusted to get a good correspondence between the logs and the base data.

Rock strength properties such as unconfined compressive strength (UCS), internal friction angle, rock cohesion (So), and tensile strength (TS) have also been calculated for Khasib formation. Using Eq. 7, the rock strength (UCS) of the Khasib formation was calculated as a function of compressional wave velocity, where UCS is in MPa [11]. A logical relationship between inputs (well log data) and outputs (Vp) is required for selecting input data[12]. Equation (8) is used to convert the sonic travel time to compressional wave velocity where Vp is the P-wave velocity in Km/sec, and Δt is the sonic time in µsec/ft. Based on the Gamma ray log, the internal friction angle is estimated for Khasib formation. Rock cohesion (S_o) and Tensile rock strength (TS) were calculated as a function of internal friction angle and rock strength.

All possible data including log data (sonic, resistivity), formation test, drilling reports, and well test are combined to determine the pore pressure profiles against the Khasib formation.

$$UCS = 2.28V_p + 1.939 \quad (7)$$

$$V_p = \frac{0.3048*10^6}{\Delta t*1000} \quad (8)$$

Pore pressure is used as a key parameter for estimating the in-situ horizontal principal stresses and for predicting safe mud weights for drilling stable wellbores without any expected results related to wellbore collapse or wellbore breakdown [13]. More than one method is normally used to estimate the horizontal stresses (Maximum σ_H and Minimum σ_h horizontal stresses). In this study, the poro-elastic models (Eqs. 9 and 10) are used to estimate the minimum and maximum horizontal stresses, respectively [14].

$$\sigma_H = (\frac{v}{1-v})(\sigma_v - \alpha\, p_p) + \alpha\, pp + (\frac{E}{1-v^2})(\varepsilon_H + v\,\varepsilon_h) \quad (9)$$

$$\sigma_h = (\frac{v}{1-v})(\sigma_v - \alpha\, p_p) + \alpha\, pp + (\frac{E}{1-v^2})(\varepsilon_h + v\,\varepsilon_H) \quad (10)$$

Where: σ_v: vertical stress, psi, v: Poisson ratio, α : Biot coefficient, pp: Pore Pressure, psi, E: Young's modulus, ε_h and ε_H are the tectonic strains in minimum and maximum horizontal stress orientations, respectively.

$$\varepsilon_H = \frac{\sigma_v v}{E}(1 - \frac{v^2}{1-v}) \quad (11)$$

$$\varepsilon_h = \frac{\sigma_v v}{E}(\frac{1}{1-v} - 1 \quad (12)$$

3.2. 3D MEM Construction

Building a three-dimensional geomechanical model depends on preparing many data, including the contour map, the wells top, the formations tops, and well heads. In addition to that, importing data from TECHLOG.2015 to Petrel software.2018.2 to build the 3D MEM, this version was used due to the difficulty of obtaining newer versions. Such these data are pore pressure, vertical and horizontal stresses, rock strength and elastic properties. In this study, the 3D structure model has been built based on fault model. Design the polygon according to the points of the Khasib contour maps. 2D grid surfaces is created depend on point data, line data, polygons, surfaces maps, and well tops. The total number of grid cells was 273024, the Z value equal to 9 based on nine layers in Khasib formation. Make upscale for the well logs utilizing arithmetic technique (simple method) based on the results that are uniform with the well logs. Kriging interpolation method was used for upscaling properties from the synthetized well logs using 1D MEM to be distributed into 3D MEM. 3D MEM enables to distribute all estimated 1D MEM parameters between wells throughout the Khasib formation. Fig. 2 shows all steps that have been used to construct the 3D MEM, which starting from building 1D MEM using well logs and correlations to constructing 3D distributions of rock mechanical properties of the Khasib formation.

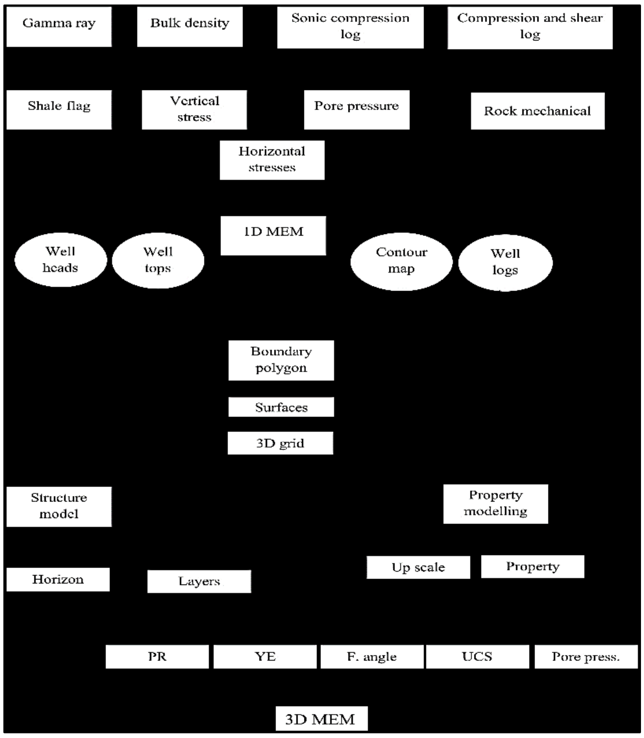


Fig. 2. 1D and 3D MEM Workflow

4- Results and Discussion

4.1. 1D MEM

A 1D MEM has been built in this study based on datasets of 4 wells of Khasib formation. Fig. 3 shows the results of the construction of geomechanical model for well B in which the elastic rock properties, rock strength, horizontal and vertical stresses, and pore pressure are presented along the depth of Khasib formation. The results of this figure revealed that the fault regime of Khasib formation can be divided into types based on the Anderson's classification. The most commonly regime is strike slip regime ($\sigma_H > \sigma_v > \sigma_h$), while the other is reverse fault regime ($\sigma_H > \sigma_h > \sigma_v$) at the top of Khasib formation and at certain depths of the Khasib formation bottom. These results showed an agreement with the information obtained from the midland oil company.

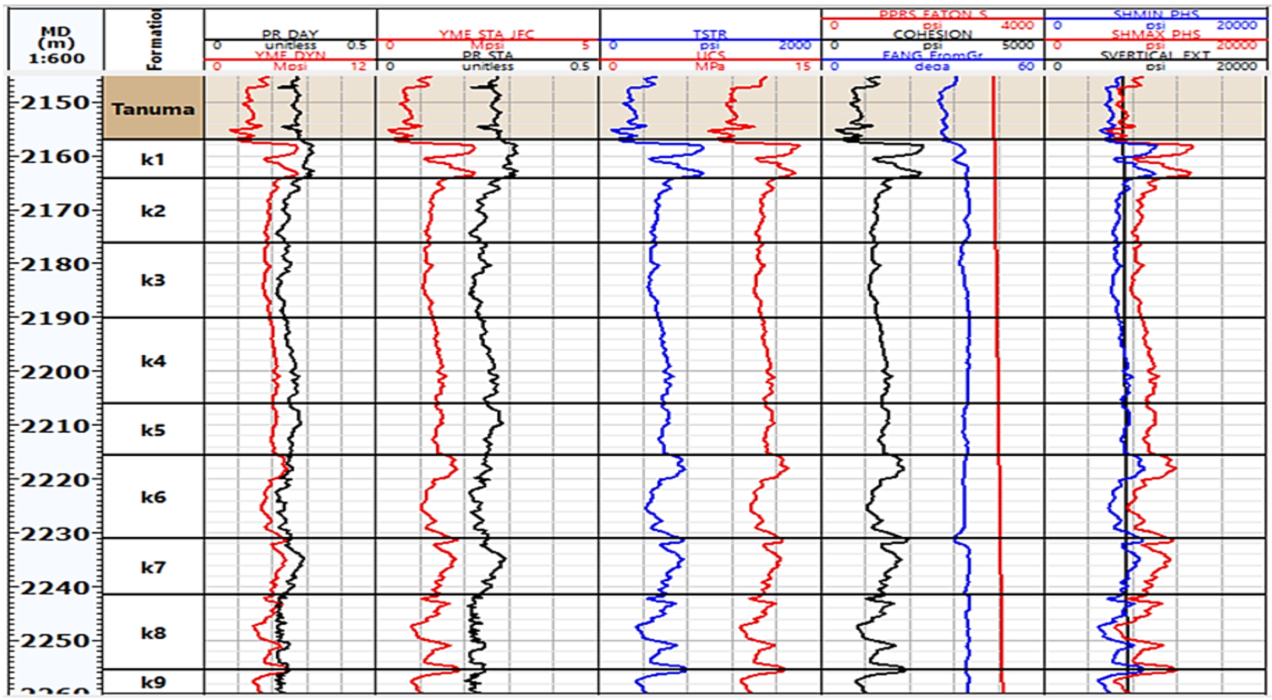


Fig. 3. 1D-MEM for Well-B

4.2. 3D MEM

a. Vertical Stress

Vertical stress (Eq. 1) represents the overlaying weight that applied at certain depth because of the rock density. Fig. 4 shows the 3D distribution of vertical stress which showed the fact that the vertical stress increases with increasing the burial depth.

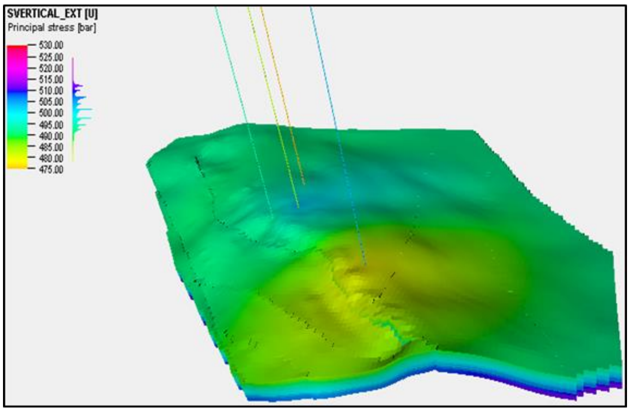


Fig. 4. 3D Distribution of Vertical Stress

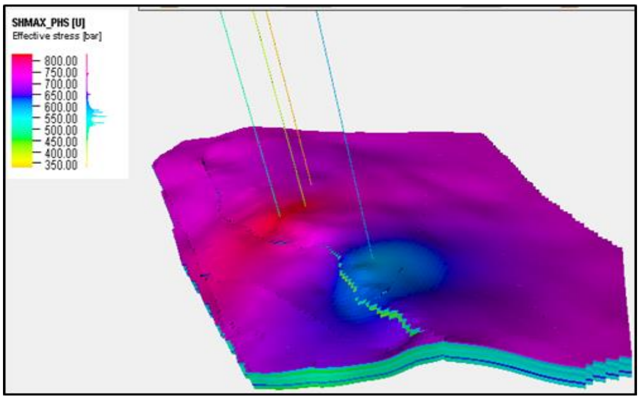
b. Horizontal stresses

Eqs. 9 through 12 have been used to quantify the magnitudes of maximum and minimum horizontal stresses for 4 wells of Khasib formation. Fig. 5 shows 3D distributions of these horizontal stresses. It is important to note that the presented stresses are effective stresses that control the strain or strength behavior of rocks and depend on the applied stresses and pore pressures. In another word, the effective stress represents the combined effect of pore pressure and total stress that keeps the particles together. The results of Fig. 5 a and b show an increase in the effective stresses around the production wells. This can attribute to the pore pressure decreasing as a result of production from four wells. For example, the magnitudes of effective maximum and minimum horizontal stresses are respectively 800 bar (11603 psi) and 625 bar (9065 psi) around the production wells. In contrast, these values are relatively less in regions far away from the production's wells.

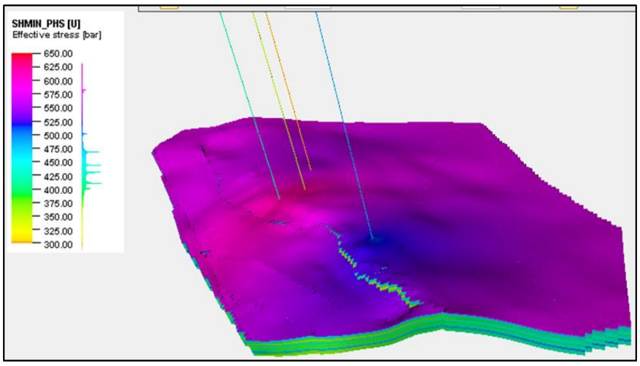
c. Pore Pressure

The 3D pore pressure distributions of the Khasib formation are shown in Fig. 6. There is a clear heterogeneity in the pressure distribution horizontally and vertically depending on the pressure of the formations. The results of this figure revealed that the magnitudes of pore pressures in the region around the production wells are less than the pore pressure magnitudes when the regions are far away from the production wells.

Fig. 7 a and b present the heterogeneity in pore pressures horizontally for two units of Khasib formation (K3 and K6). Based on the results of Fig. 7, the pore pressure distribution in the Khasib formation can be divided into two regions. High and low pressured zones. the first region has a high value of pore pressure, while the second region has low pressure values. This difference is because most of the production wells are concentrated in the second region. The pore pressure of the Khasib formation ranges between 3100 psi at the top and about 3500 psi at the bottom. This gives a good agreement with the 1D and 3D MEM results. Fig. 6 a and b, show the pore pressure distributions in the layers K3 and K6 of Khasib formation, respectively.



(a)



(b)

Fig. 5. a. 3D Distribution of Maximum Horizontal Stress b.3D Distribution of Minimum Horizontal Stress

d. Poisson's ratio

Poisson’s ratio is an important mechanical property since it is used to figure out the geomechanical behavior of well drilling and subsequent operations [15]. Fig. 8, shows the 3D distribution of the Poisson ratio of Khasib formation. Fig. 9 a, shows higher values of Poisson’s ratio (0.3 – 0.31) in layer K1 since this layer has low porosity and permeability due to its high rock cohesion and hardness. In contrast, other layers have almost the same values of Poisson’s ratio as shown in Fig. 9 b for layer K4.

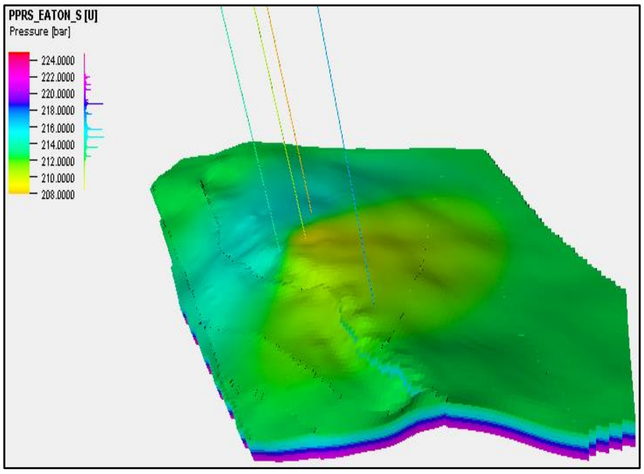


Fig. 6. 3D Distribution of Pore Pressure

e. Young's modulus

Young's modulus represents the hardness of the rock. There is a clear vertical and horizontal heterogeneity of Young’s modulus values in Khasib formation, Fig. 10. The highest value of Young’s modulus is shown at the top of reservoir and that show in layer K1 (10.2 – 13.2 GPa), Fig. 11 a. This layer is more stiffness than other layers that have high porosities and permeabilities and that contain hydrocarbon as in K3 layer of Khasib formation Fig. 11b. This means that the strength of the rock is weak due to the presence of voids inside the rock structure, resulting a lower stiffness in the rock (6.9 to 8.9 GPa) (i.e., higher deformation of the rock when the stresses are applied) as shown in Fig. 11 b.

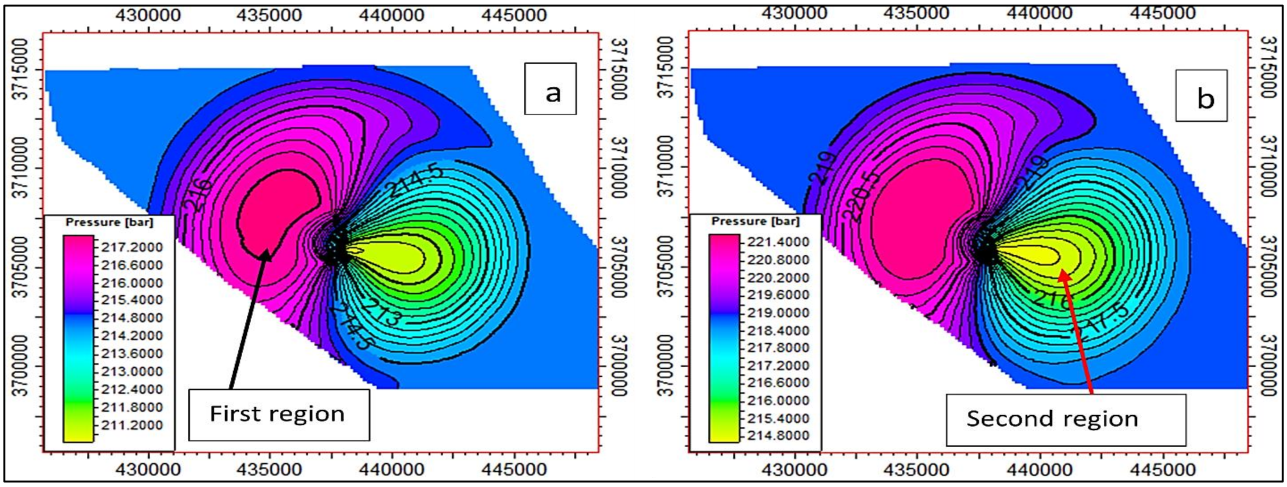


Fig. 7. 2D Contour Map of Pore Pressure Distribution, a) K3, b) K6

f. Unconfined Compressive Strength (UCS) And Tensile Strength

Unconfined compressive strength (UCS), as one of the main parameters in reservoir geomechanics, represents the strength of the rocks or the rock withstanding to the applied stress. Fig. 12, illustrates the 3D distribution of UCS of Khasib formation. The results showed a higher UCS at the top of the Khasib formation (i.e., layer K1) as a comparison with other layers. The reason is similar to that reason in interpreting the higher values of Young's modulus and Poisson's ratio. The rock strength of layer K1 is ranged between 117 and 130 bar Fig. 13 a, while it is between 96 and 112 bar in layer K2, Fig. 13 b. This means that layer K1 is a more compacted carbonate layer than other layers of Khasib formation.

The tensile strength of Khasib formation has the same behavior as UCS because it depends on UCS in the calculation. Fig. 14 presents a 3D distribution of tensile strength of Khasib formation while Fig. 15 a and b presents a 2D distribution of K1 and K2 layers, respectively.

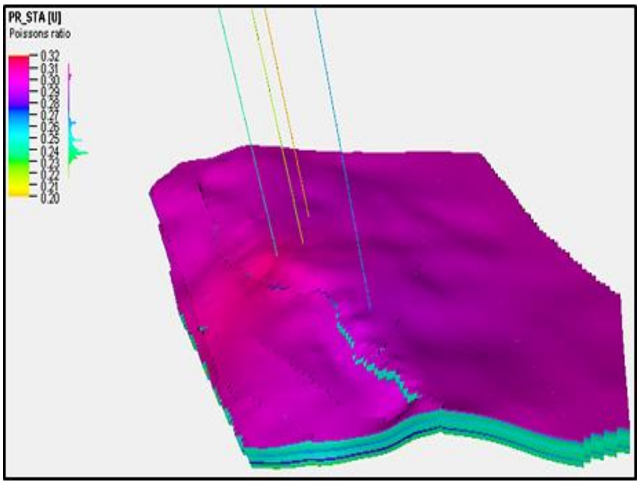


Fig. 8. 3D Distribution of Poisson's Ratio

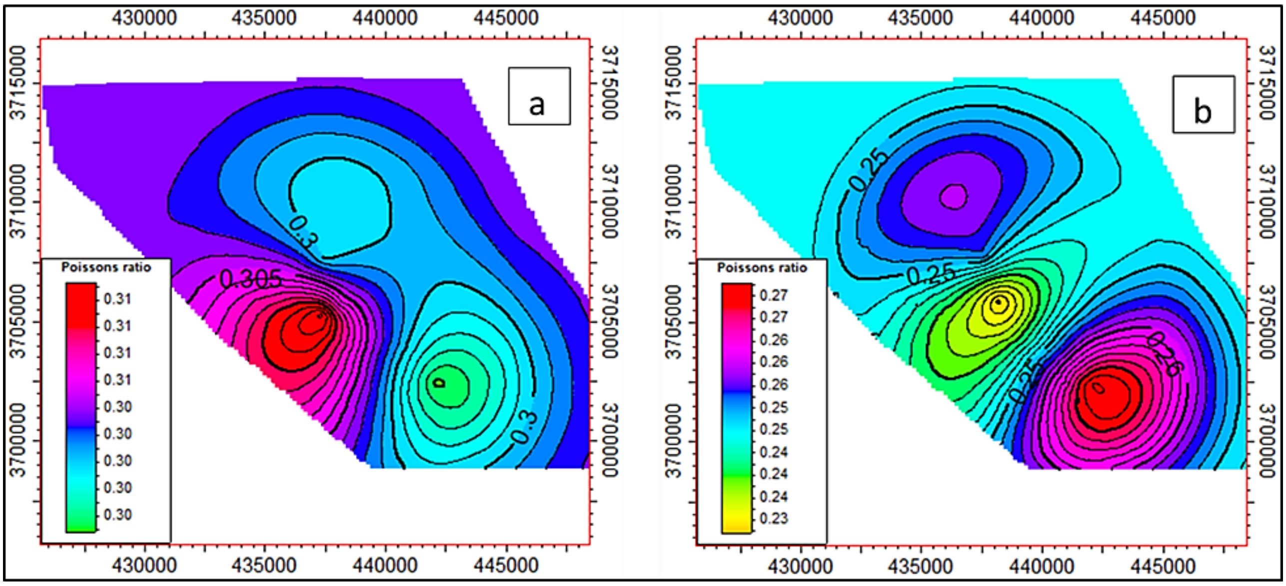


Fig. 9. 2D Contour Map of Poisson Ratio, a) K1, b) K4

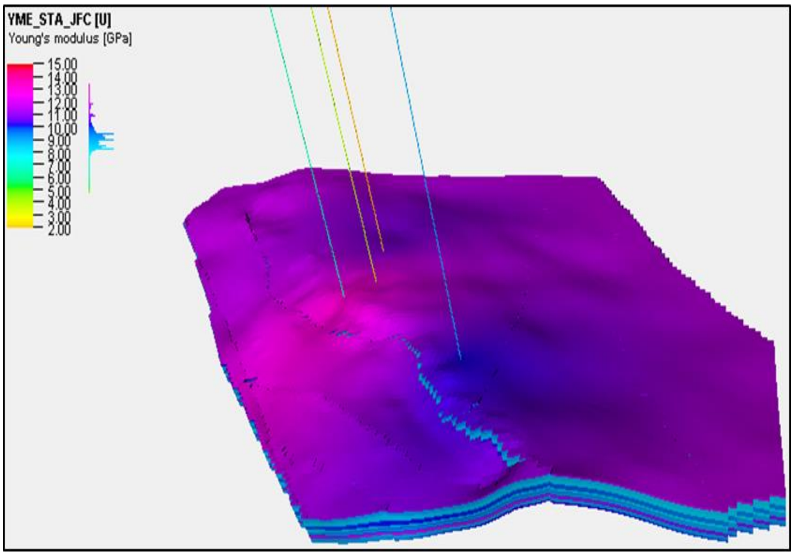


Fig. 10. 3D Distribution of Young's Modulus

g. Friction angle

Fig. 16 shows the 3D results of the friction angle of the Khasib reservoir which are ranged between 38° and 40°. This range agrees with the basic range of friction angle for carbonates (21.5° - 41.3°) [16]. Fig. 17 a and b. represent the 2D distributions of friction angle for layer K3 and K8, respectively.

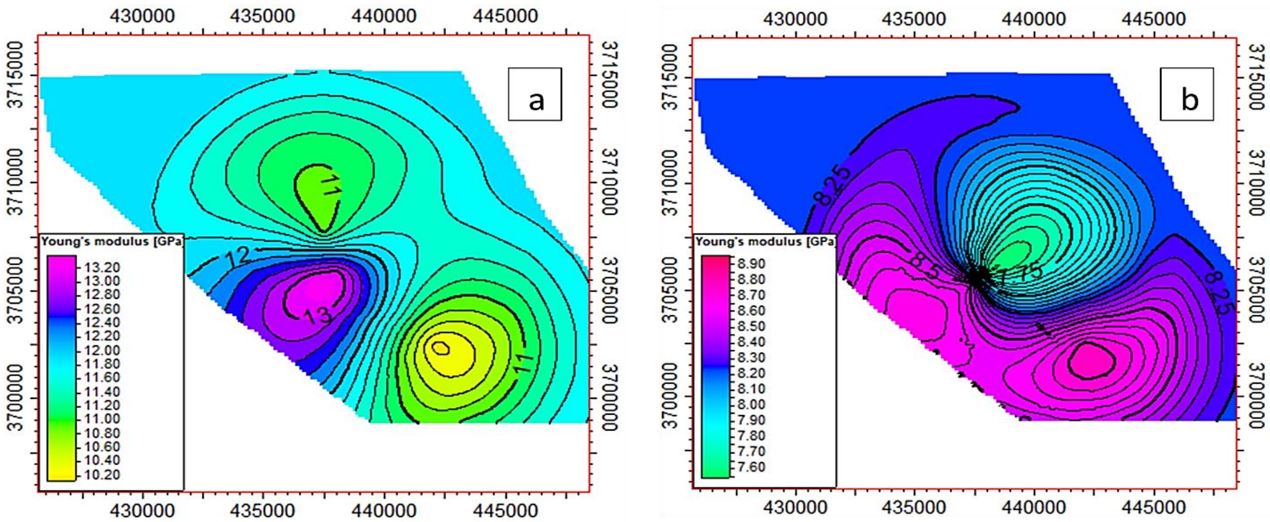


Fig. 11. 2D Contour Map of Young's Modulus, a) for Layer K1, b) for Layer K3

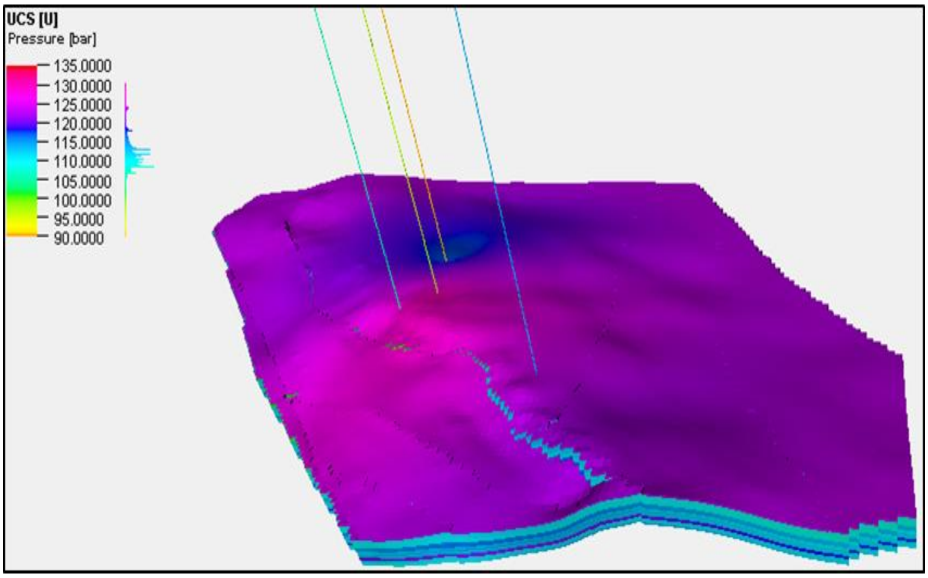


Fig. 12. 3D Distribution of UCS

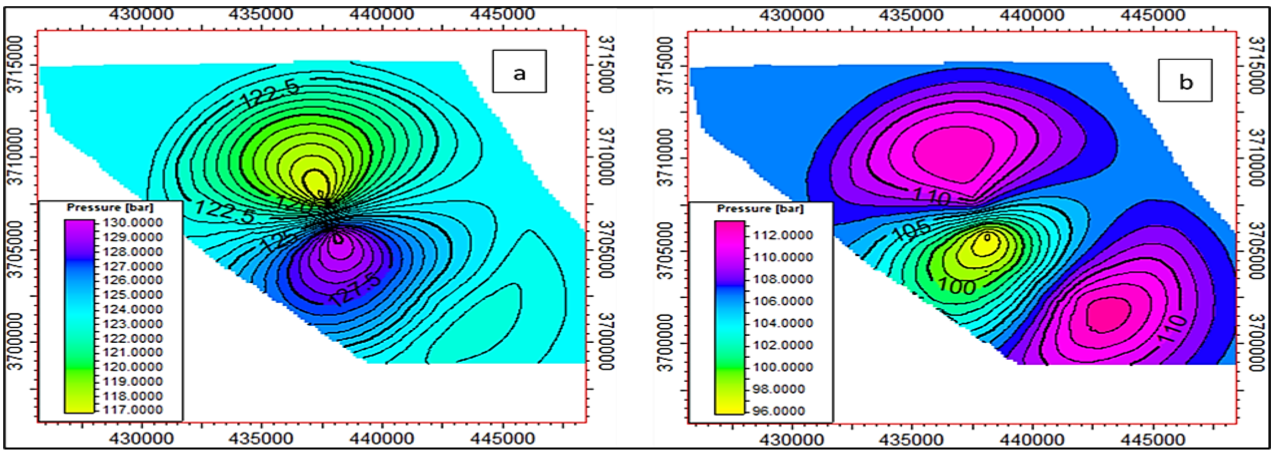


Fig. 13. 2D Contour Map of UCS, a) Layer K1, b) Layer K2

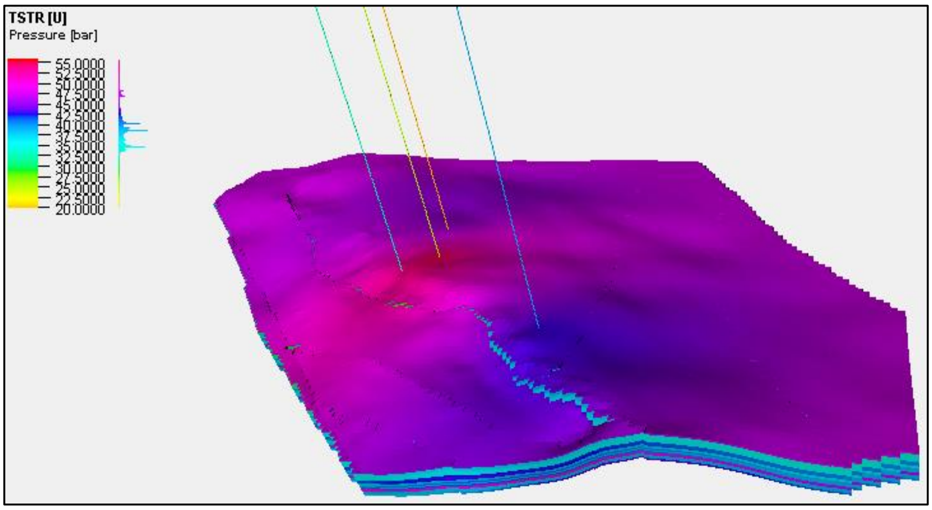


Fig. 14. 3D Distribution of TSTR

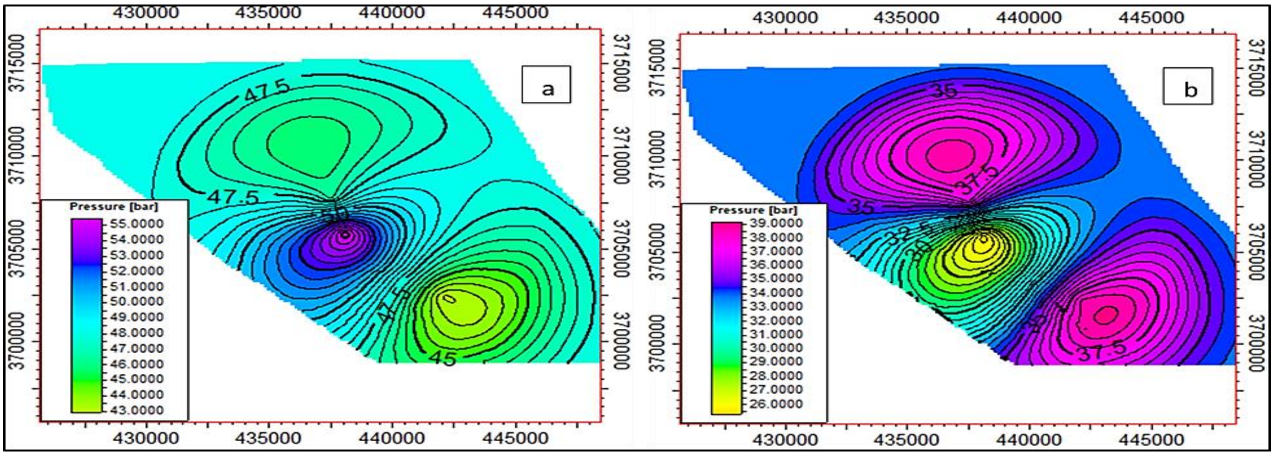


Fig. 15. 2D contour map for TSTR

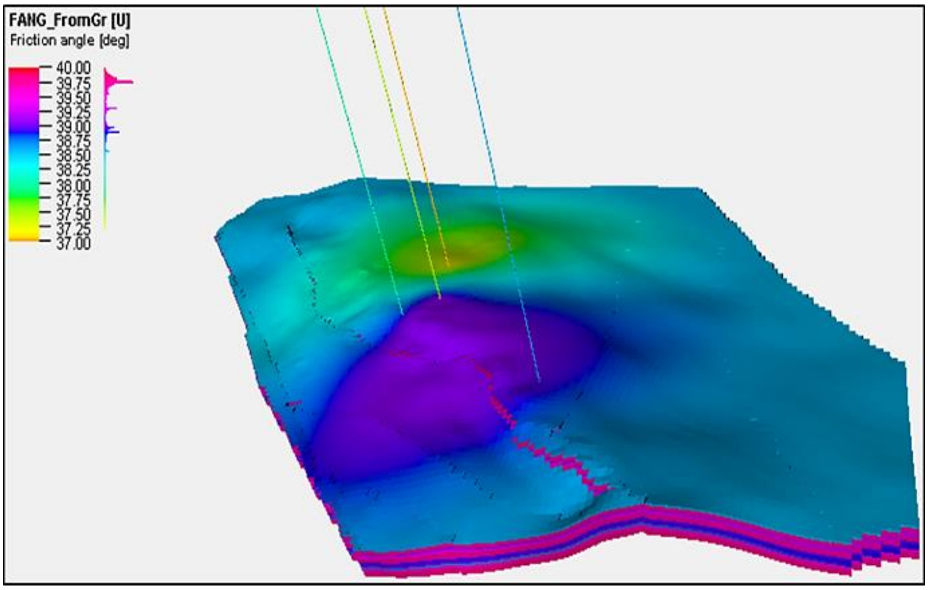


Fig. 16. 3D Distribution of Friction Angle

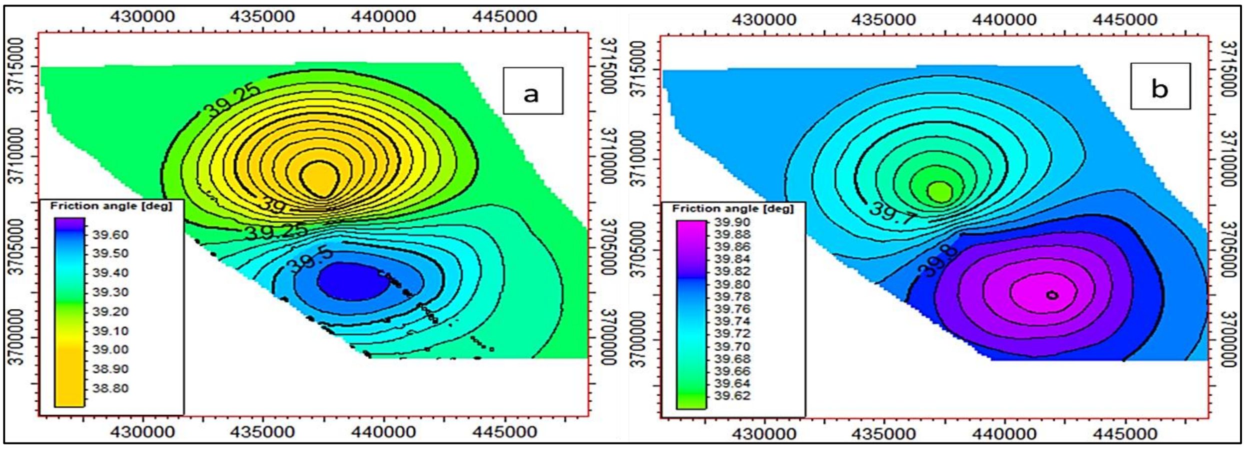


Fig. 17. 3D Contour Map of Friction Angle, a) Layer K3, b) Layer K8

5- Summary

A summary distribution of all mechanical properties for all layers showed that the highest values of rock mechanical properties appear in the k1 and K7 layers, while other layers have approximately a closest distribution or similar distribution in the rock mechanical properties. This is due to the cohesion and cementing between the layer components. Table 1 show the most likely values of all mechanical properties.

Table 1. The Most Likely Values of All Properties

Parameters	K1	K2	K3	K4	K5	K6	K7	K8	K9
Thickness (m)	6	12.5	15	14.5	7	14.5	9.5	12	7
E (Mpsi)	1.7	1.2	1.19	1.36	1.18	1.3	1.45	1.32	1.36
UCS (psi)	1800	1572	1587	1661	1617	1640	1734	1620	1600
PR	0.3	0.264	0.236	0.248	0.242	0.237	0.264	0.24	0.233
C_O (psi)	1752	1250	1220	1380	1230	1340	1600	1337	1352
Θ_f (deg)	38.6	39.7	39.3	39.7	39	38.95	39.5	39.78	39.83

6- Conclusions

This study presents 2D and 3D distributions of rock mechanical properties of the Khasib formation in the East Baghdad oil field/ Central area. The results outcomes can be summarized by the following points:

1. The horizontal stresses are somewhat similar for all layers in the vertical case, but their distribution is horizontally varied due to the change in pore pressure.
2. Based on the 2D distributions of pore pressure of K3 and K6 units, the Khasib formation of East Baghdad oilfield/ central area can be divided into two regions, the first region with relatively high values of pore pressures, while the second region has low values of pore pressure. This difference is because of most of the production wells are concentrated in the second region.
3. Elastic characteristics of Khasib formation including Poisson ratio and Young modulus have the same behavior, the highest value of the parameters appeared in the surface unit (k1). This layer is stiffer than other layers that have high porosities and permeabilities and that contain hydrocarbon.
4. Higher values of UCS are observed in the K1 layer rather than in other layers, also the tensile strength has the same behavior because it depends on UCS calculation.
5. The internal friction angle for all layers within the Khasib reservoir ranges between 38°-40°, this gives a good harmonization with the limestone friction angle.

NOMENCLATURE

σ = Normal stress Psi
ε = Strain Unitless
τ = Shear stress Psi
σ' = Effective stress Psi
σV = Vertical stress Psi
σH = Maximum horizontal stress Psi
σh = Minimum horizontal stress Psi
Pp = Pore pressure Psi
UCS = Unconfined compressive strength Mpa
φ, FANG = Internal friction angle degree
To, TSTR = Tensile strength Psi
Co, So = Cohesive strength Psi
ν, PR = Poisson's ratio Unitless
E, YME = Young's modulus Mpsi
$Edyn$ = Dynamic Young's modulus Mpsi
G = Shear modulus Mpsi
K = Bulk modulus Mpsi
ρb = Bulk density gm/cc
ΔT = Sonic transit time us/ft
α = Biot constant Unitless

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النمذجة الثنائية والثلاثية الأبعاد للخصائص الميكانيكية الصخرية لمكمن الخصيب في حقل نفط شرق بغداد

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الخلاصة

تُعد معرفة توزيع خصائص الصخور الميكانيكية والضغوط في الحقل وظيفة مهمة للعديد من التطبيقات المتعلقة بجيوميكانيكية المكامن، بما في ذلك تحليل عدم استقرار حفرة البئر، والتكسير الهيدروليكي، وإنتاج الرمل، وتراص المكمن والهبوط. يتمثل التحدي الرئيسي في تحديد خصائص الصخور الميكانيكية في أنه لا يتم حسابها عند البئر مباشرة. علاوة على ذلك، فإن العينات الكربونية المستخلصة لأجراء القياسات المختبرية محدودة وتوفر بيانات منفردة لأعماق محددة.

الغرض من هذه الدراسة هو بناء موديلات جيوميكانيكية ثنائية وثلاثية الأبعاد لمكمن الخصيب في حقل نفط شرق بغداد / المنطقة الوسطى. تم استخدام برنامج TECHLOG.2015.3 لبناء الموديل الجيوميكانيكي احادي الابعاد بينما تم استخدام برنامج Petrel E&P 2018.2 لبناء الموديل الجيوميكانيكي ثلاثي الأبعاد للخصائص الميكانيكية للصخور. يتكون تشكيل الخصيب من تسع وحدات (K1–K9). تدعم النتائج الحالية الدليل على أن الاجهادات الأفقية متشابهة إلى حد ما لجميع الطبقات في الحالة العمودية ، لكن توزيعها يختلف أفقياً بسبب التغيرات في ضغوط المسامية. يزداد ضغط المسامي عموديًا، لكن توزيعه داخل الطبقة الواحدة يختلف بسبب الإنتاج من ابار مختلفة. تتمتع خصائص المرونة والقوة للصخور، ومعامل يونغ، ونسبة بواسون، و UCS بنفس السلوك، حيث ظهرت أعلى قيمة لهذه المعاملات في الطبقة السطحية (K1). تتراوح زاوية الاحتكاك الداخلي لجميع الوحدات بين ٣٨° و ٤٠°، وهذا يعطي انسجامًا جيدًا مع زاوية احتكاك الحجر الجيري. التوزيع الثلاثي أشار الى عدم تجانس الصخور الكربونية بسبب بيئتها الترسيبية البحرية وعمليات الدايجينتك المعقدة. نتائج هذه الدراسة يمكن استخدامها في التطبيقات الجيوميكانيكية المستقبلية في حقل شرقي بغداد من ضمنها استقراريه جدار البئر، إعادة تنشيط الصدع وحبس ثنائي أوكسيد الكاربون.

الكلمات الدالة: الموديل الجيوميكانيكي الأحادي والثلاثي الابعاد، مكمن الخصيب، حقل نفط شرقي بغداد، خصائص الصخور الميكانيكية.