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Using well log data to predict rock compressibility and elasticity in Zubair formation/ southern of Iraq

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Abstract

The mechanical characteristics of rocks such as elasticity (Young's modulus, Poisson's ratio, and unconfined compressive strength) play an essential in sand production analysis, well design, and borehole stability assessment. In this study, the mechanical characteristics of rocks were indirectly estimated using gamma ray, density, and acoustic (compressional and shear) log data from well RU-X in the Rumaila oil field, specifically for the Zubair Formation. These estimated properties were compared to direct measurements obtained from triaxial and uniaxial mechanical tests conducted on well RU-X. The results showed a significant similarity between the indirect estimates and the direct measurements, indicating their reliability for sand production analysis and their valuable contribution to constructing the geomechanical model. Moreover, the static profile of Poisson's ratio was validated using laboratory core test results, demonstrating reasonable agreement. The validation process involved comparing laboratory-derived measurements with actual field measurements in the Zubair Formation. The higher Poisson's ratio observed in the shale was attributed to the slower propagation of acoustic waves, resulting in a good matching with an R^2 value of 0.77. On the other hand, the lower Young's modulus in the shaly formations indicated lower resistance to deformation, with a comparative ratio of R^2=0.96. Static measurements, which consider various influencing factors, provide a more realistic representation of rock behavior under different conditions. Regarding unconfined compressive strength, the comparative ratio was R^2=0.83.

Keywords: Rumaila oilfield; Zubair Formation; Poisson's ratio; Gamma Ray Log.

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1- Introduction

In every geomechanical analysis aimed at determining the optimal design to reduce sand production, optimize well completion, and plan production facilities, rock mechanical parameters such as the modulus of elasticity and compressive strength are essential components [1]. During the evaluation of geological formations, well log data plays a crucial role. Shear velocity is particularly important in geomechanical investigations, petrophysical property calculations, seismic exploration, and well stability evaluation [2]. When a force or influence that distorts a body is removed, the body's ability to resist that force or influence allows it to regain its normal size and shape. Hooke's law is a fundamental rule that defines the behavior of elastic substances. It states that for tiny distortions, there is a straight line between the applied stress and the resulting strain. In the context of rocks, several elastic characteristics for instance Poisson's ratio (ν), Young's modulus (E), shear modulus (G), and bulk modulus (K) are used to explain their elastic distortion under load [3]. On the other hand, dynamic methods utilize the propagation of acoustic waves in rocks to estimate their elastic characteristics. It is feasible to estimate the values of elastic properties including Young's modulus, Poisson's ratio, shear modulus, and bulk modulus by measuring the acoustic wave velocity and fusing this data with density logs [4]. This method has benefits in terms of cost, availability of data, and the capacity to forecast rock mechanical properties at various depths [5, 6]. Young's modulus represents the material's rigidity and relates uniaxial stress to strain. It quantifies the material's resistance to deformation under axial loading. Poisson's ratio, on the other hand, indicates the contraction or extension of a material parallel to the direction of the applied load. It provides information about how strain is distributed in the material when subjected to a load [7]. Compressive strength reflects the stress at which rock begins to deform in compression tests. Understanding rock strength is crucial for stress analysis and predicting shear strength, tensile strength, and uniaxial compressive strength [8]. The mechanical properties of the Zubair Formation were determined in this study using wireline data, including acoustic compressibility wave, acoustic shear wave, and density measurements. The findings were subsequently validated by test results obtained through the analysis of core samples. Log data can be utilized to indirectly evaluate the mechanical parameters of the formation.

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2- Area of the study and its geological setting

Rumaila oilfield is one of the greatest oilfields in Iraq which is located about 50 km to the west of Basra city, Southern Iraq, and 32 km from the Kuwait border as shown in Fig. 1 [9]. It was discovered in 1953 and currently contributes to 33% of Iraq's total oil production with reserves of 17 billion barrels [10].

The north part of Rumaila oilfield has two main producing reservoirs which are the Mishrif Formation and Zubair Formation as shown in Fig. 2 [11]. This study will emphasize on Zubair Formation, which is considered to be the main producing unit in the North Rumaila Oilfield in southern Iraq [12, 13].

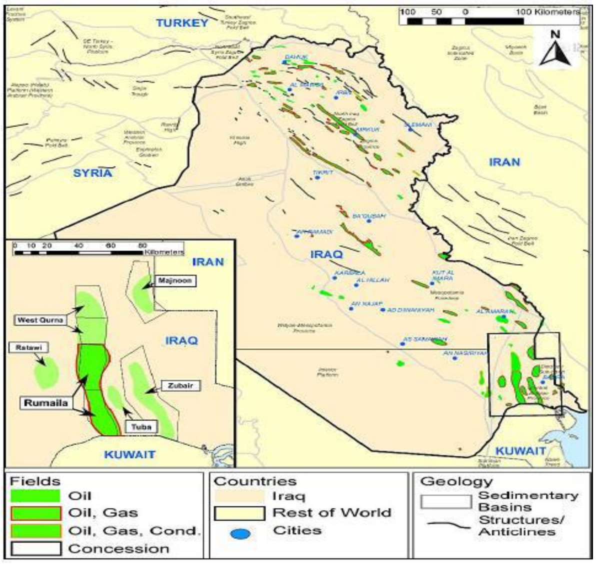

Fig. 1. The Rumaila Oilfield Location (Area of Study) [8]

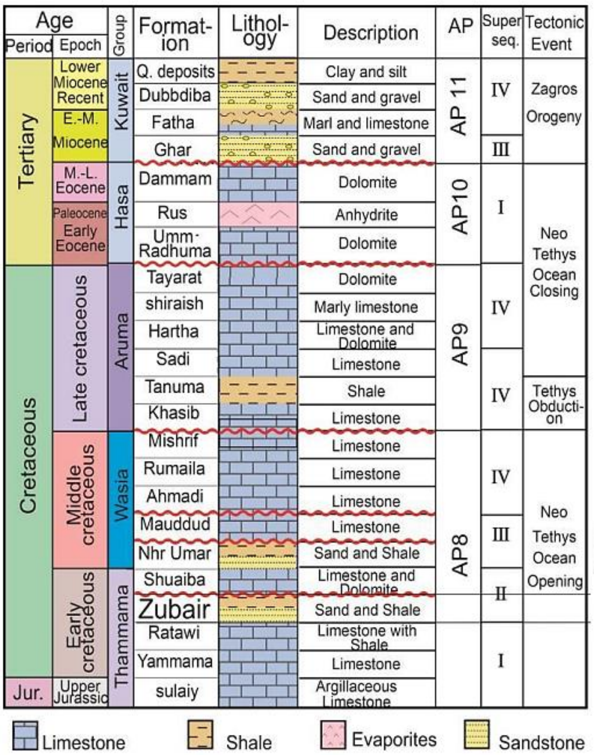

Fig. 2. Stratigraphic Map for North Rumaila Oilfield [11]

3- Methodology

Direct (or static) and indirect (or dynamic) methods are commonly employed to measure the mechanical characteristics of rocks. Direct measurements involve laboratory experiments using specialized equipment and core samples to analyze rock strength and elastic properties through petrophysical analysis [12]. On the other hand, indirect methods utilize data obtained from well logs, including shear and compressional wave velocities derived from sonic logs.

Static methods are often considered straightforward and are conducted in a laboratory setting. They provide valuable insights into rock mechanical properties. Dynamic methods, however, provide the benefit of being continuous and relatively easy to implement. Hence, a comprehensive study of rock mechanical characteristics requires a combination of laboratory experiments and well-logging approaches [12]. The estimates of rock strength obtained from well log data can be further validated using laboratory test results [14].

- Static measurements using core data

One of the direct methods used to determine rock failure criteria and assess compressive and elastic properties is the Triaxial Compression Strength (TCS) test. In this test, a cylindrical core sample with a one-inch diameter and a two-inch length is placed inside a non-permeable sleeve that has been saturated with mineral oil, is shown in Fig. 3 [14]. The sleeve sample is then placed under an identified confining pressure (S3=S2) and gradually applied to an increasing axial load (S1) for the next few steps. The test continues to be carried out until it fails. It is important to note that lower confining pressures result in lower failure loads, as the confining pressure directly affects the collapse loads [15].

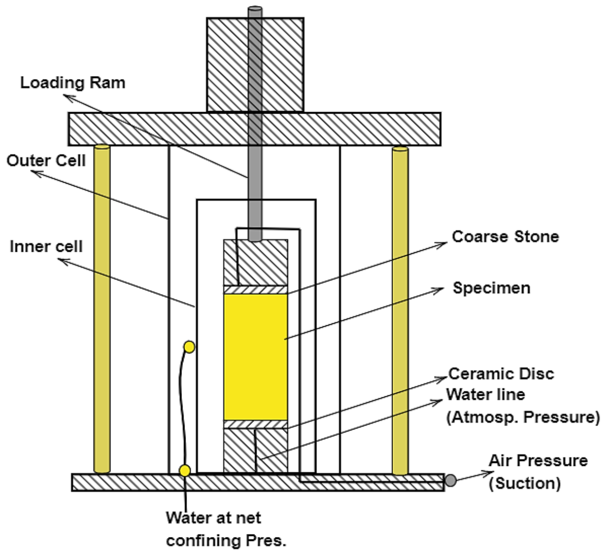

Fig. 3. Arrangement for Triaxial Test [14]

The uniaxial test, which offers useful information about rock mechanical properties, is the second type of test recognized by the International Society of Rock Mechanics (ISRM). The setup for this test requires utilizing a loading frame to support a cylindrical core sample. The test core sample's dimensions are 20 inches long and 10 inches in diameter, as shown in Fig. 4 [16].

During the uniaxial test, the core sample is subjected to an axial load that is incrementally increased until deformation occurs. Throughout the test, the applied stress and resulting strain are systematically measured and recorded. The Uniaxial Compressive Strength (UCS) is a crucial parameter obtained from this test, representing the maximum axial compressive stress that an unbound rock cylinder can endure without failure [16]. The UCS value provides valuable insights into the rock's strength and its ability to withstand compressive forces.

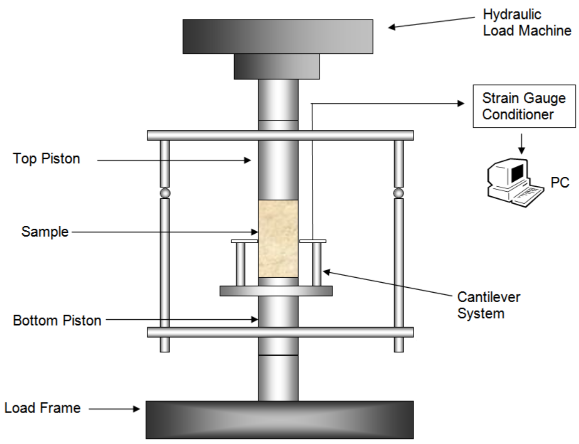

Fig. 4. Uniaxial Compression Test Equipment [16]

- Dynamic measurements using log Data

Using the Schlumberger Techlog, different correlations have been identified to define rock mechanics. One of these connections involves the use of John Fuller's method [18]. It compares changing dynamic and static models using well logs depending on the compressional wave velocity (V_P) and shear wave velocity (V_s) [19, 20]. The transit time or slowness of compressional waves (Δt_p) and shear waves (Δt_s) can be determined from recorded acoustic waveforms. Well logs provide continuous measurements of these wave velocities, allowing for the estimation of rock elastic characteristics at different depths [21].

By utilizing the dynamic values obtained from acoustic logs, it becomes possible to determine critical rock mechanical characteristics. such as Poisson's ratio and Young's modulus. However, to calculate the bulk modulus (K) and shear modulus (G), the values of Poisson's ratio and Young's modulus need to be determined first. Techlog 2021 program relied on the following equations to calculate rock mechanical properties [18, 22].

$$G_{dyn} = \frac{\rho_b}{\Delta t_s^{\ 2}} \quad (1)$$

$$K_{dyn} = \frac{\rho_b}{\Delta t_p^{\ 2}} - \frac{4}{3}\, G_{dyn} \quad (2)$$

Where: ρb: is bulk density (g/cm³). Δt_p: is Compressional sonic wave µs/ft. Δt_s : is shear slowness µs/ft. K_{dyn} and G_{dyn} are in MPa.

Young's modulus (E) can be determined by utilizing empirical relationships between the bulk modulus (K) and shear modulus (G). The shear modulus can be calculated by employing shear velocity and density logs [23, 24]. Young's modulus and Poisson's ratio are computed based on the shear and bulk modulus values using Eqs. 3 and 4 as follows [18, 25].

$$E_{dyn} = \frac{9Gdyn \times Kdyn}{Gdyn + 3kdyn} \quad (3)$$

$$V_{dyn} = \frac{3Kdyn - 2Gdyn}{6Kdyn + 2Gdyn} \quad (4)$$

Poisson's ratio (ν) is a dimensionless quantity, meaning it has no units. On the other hand, Young's modulus (E) is typically measured in units of Mega Pounds per Square Inch (Mpsi).

The compressive strength of the rocks can be estimated using the technology program, which is based on a set of equations, including Eq. 5, which depends on the variable △Tp [26]

$$UCS = 0.203 * \triangle Tp^{4.2267} \quad (5)$$

Where: UCS is unconfined compressive strength. △Tp: is Compressional sonic wave µs/ft.

4- Results and discussions

A triaxial compressive strength (TCS) test was conducted on a single core plug extracted from the Zubair Formation at the RU-X well to assess its static elastic properties, specifically Young's modulus and Poisson's ratio. The results of the triaxial test are summarized in Table 1.

In addition, in situ tests were performed to confirm. The compressive strength characteristics of core plugs represent the Zubair Formation in RU-X wells. Both the Uniaxial Compression Test (UCT) and the Triaxial Compressive Strength (TCS) test were carried out. Table 2 provides a summary of the outcomes from the core plugs' Uniaxial Compression Test (UCS). These experiments were conducted by the Rumaila Operating Establishment.

Table 1. Results of the Well RU-X's Triaxial Test in the Rumaila Oil Field

Depth (m)	Formation	Young Modulus (Mpsi)	Poisson's ratio (unitless)
3186	Zubair	3.29	0.37
3248	Zubair	2.91	0.19
3260	Zubair	1.8	0.2
3365	Zubair	3.96	0.15
3396	Zubair	4.67	0.3

Table 2. Results of a Uniaxial Compression Test in RU-X

Core Depth (m)	Formation	UCS (psi)
3183	Zubair	2426
3249	Zubair	6562
3400	Zubair	11998

- Dynamic values for rock mechanical characteristics are obtained

The disparity between dynamic and static elastic values can be attributed to several factors. Firstly, different strain ranges in various measurement approaches lead to a nonlinear elastic response, which explains the difference. Additionally, the presence of porosity, fractures, and variations in spatial bedding plane orientation also influence the measurements, further contributing to the variation between static and dynamic modulus values [22, 27].

In the case of uniformly elastic materials like steel, the characteristics of static and dynamic elasticity are equivalent, highlighting the role of rock microstructure variability in causing the disparity [15, 28].

To estimate the shear modulus and dynamic mass values in the RU-X well, Eqs. 1 and 2 can be utilized. Subsequently, based on the results, dynamic Young's modulus and Poisson's ratio can be calculated using Eqs.3 and 4, respectively.

The correlation between the predicted dynamic elastic properties obtained from log data for the RU-X well and the static elastic values derived from core tests reveals significant relationships. These relationships have been established through correlation studies between elastic characteristics which are dynamic and static, providing the subsequent relationships [29, 30].

$$E_{sta}= 1.415E_{dyn} -1.5102 \tag{6}$$

$$V_{sta} =0.6879V_{dyn}+ 0.0955 \tag{7}$$

E_{sta}, E_{day}: dynamic, Static Young's modulus respectively (Mpsi). V_{sta}, V_{day}: Static, dynamic Poisson's ratio respectively (dimensionless).

Using the empirical relationships described in Eqs. 6 and 7, we estimated the constant Young's modulus and Poisson's ratio. Since shear wave data was not available in shallow formations, we combined density log data in the Rumaila oil field (RU-X) with compression and shear acoustic data for the Zubair Formation. This data integration allowed us to calculate the shear modulus and mass using Eqs. 1 and 2. Subsequently, it applied Eqs.3 and 4 to determine the dynamic Young's modulus and Poisson's ratio based on the available data. Fig. 5 to Fig. 7 showed the relation between the core and well log data for young modulus, Poisson's ratio, and UCS for Zubair formation. Fig. 8 to Fig. 10 represent a comparison Analysis of Static and Dynamic geomechanical properties versus depth for well RU-X.

It has been observed that the Poisson's ratio values in the Zubair Formation/Upper Shale, both static and dynamic, are higher compared to those in less-shale intervals. This discrepancy can be attributed to the fact that sonic waves return to the shale formation at a lower velocity, resulting in longer transit times for shear and compressional waves. It is important to note that the transit time is inversely related to velocity, and this relationship plays a crucial role in calculating the Poisson's ratio. In comparison, shale formations have a lower Young's modulus. This difference could be due to various factors such as stress-strain rate, cementation, pore pressure, and amplitude. Schlumberger Techlog introduced YME_STA_JFE in 2021, a correlation using Young's modulus to assess the UCS of both clay and grain-supported rocks. Notably, UCS values show an increase in sand regions, indicated by lower GR readings. These UCS values are validated through fundamental sample tests, ensuring precise and reliable results. Both dynamic and static measurements exhibit close alignment and agreement. Based on our findings, it can be concluded that the static measurements closely and significantly align with the dynamic measurements. This suggests that dispensing with static measurements is a viable option due to several reasons: the unavailability of the ball in all wells, the high associated economic cost, and the fact that the dynamic method yields similar or nearly identical results while providing cost savings.

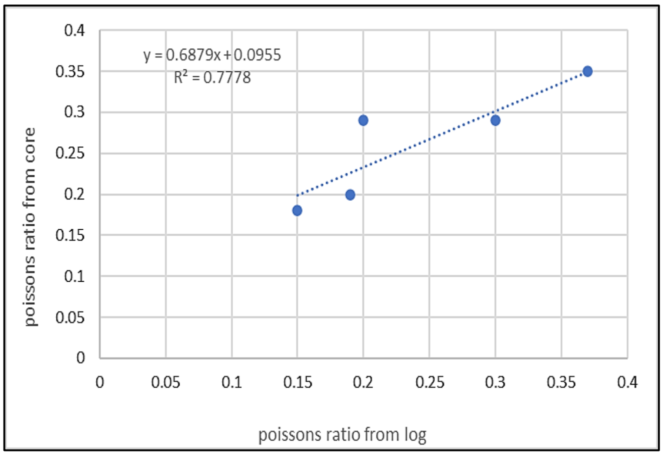

Fig. 5. Comparisons Between Static and Dynamic Poisons Ratio

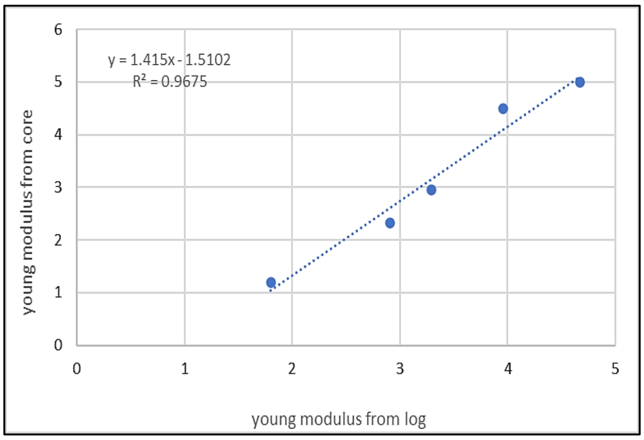

Fig. 6. Comparisons Between Static and Dynamic Young's Moduli

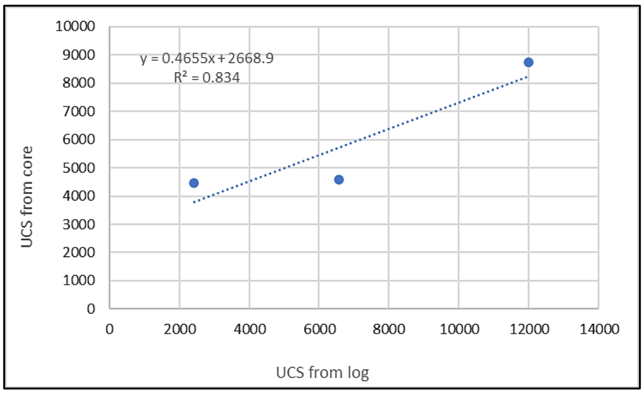

Fig. 7. Comparisons Between Static and Dynamic Unconfined Compressive Strength

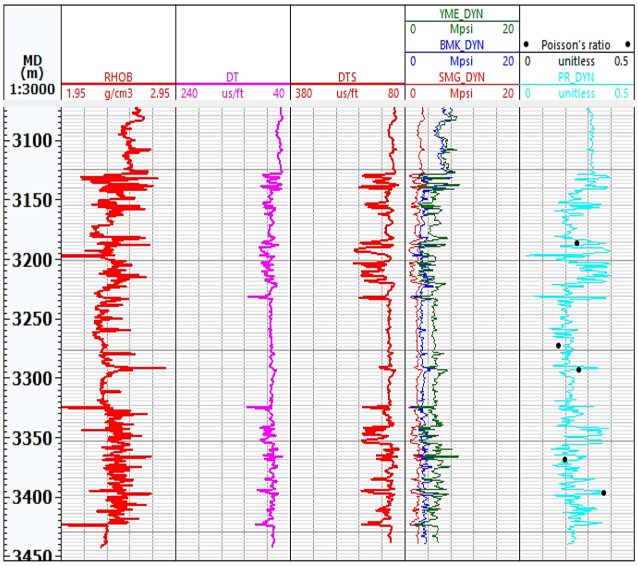

Fig. 8. Comparative Analysis of Static and Dynamic Poisson's Ratio in Wells RU-X

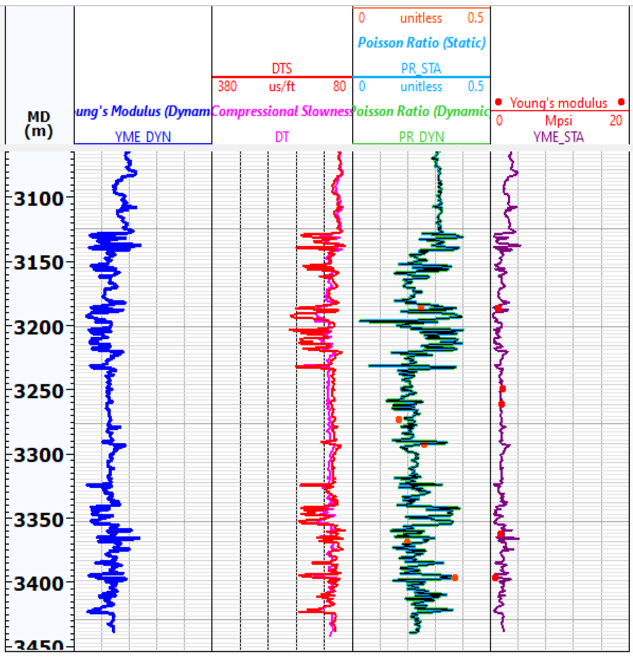

Fig. 9. Comparative Analysis of Static and Dynamic Young's Modulus in Wells RU-X

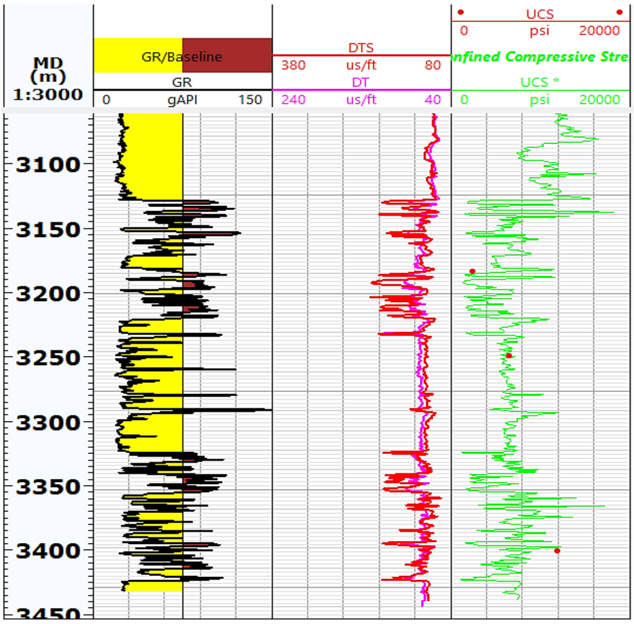

Fig. 10. Comparative Analysis of Static and Dynamic Compressive Strength (UCS) Values in Wells RU-X

5- Conclusions

Determining the requirements for sand production requires a deep understanding of the mechanical properties of rocks, such as elasticity and compressive strength. This study aimed to investigate the feasibility of indirectly predicting rock mechanical properties in the Rumaila oil field by analyzing well log data, specifically density logs and acoustic logs. The study involved calculating dynamic values of Young's modulus (E), Poisson's ratio (v), and rock compressive strength (UCS) and comparing them to results obtained from direct tests on core samples, including uniaxial and triaxial tests. The static Poisson's ratio was validated using laboratory core test results. In the Zubair Formation/Upper Shale, shale exhibited a higher Poisson's ratio due to slower sonic waves, while shaly formations had a lower Young's modulus. Static values were found to be more realistic, influenced by factors such as stress-strain rate, cementation, pore pressure, and amplitude. The dynamic and static measurements were found to closely align. Thus, it is suggested that dispensing with static measurements is a viable option due to limited ball availability, high costs, and comparable results from the dynamic method.

Abbreviation

E: Young modulus
G: Shear Modulus
ISRM: International Society of Rock Mechanics
K: Bulk Modulus
UCS: Unconfined compressive strength
Vp: Compressional wave velocity
Vs: Shear wave velocity
Δt: Acoustic travel time

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استخدام بيانات مجسات الابار للتنبؤ بأنضغاطية ومرونة الصخور في طبقة الزبير في جنوب العراق

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الخلاصة

تعتبر الخصائص الميكانيكية للصخور، بما في ذلك المرونة (معامل يونغ E، ونسبة بواسون V، وقوة الانضغاط غير المحصورة) UCS ضرورية في تحليل إنتاج الرمال وتصميم الآبار وتقييم استقرار البئر. في هذه الدراسة، تم تقدير الخصائص الميكانيكية للصخور بشكل غير مباشر باستخدام أشعة كاما، والكثافة، وبيانات السجل الصوتية (الانضغاطية والقص) من بئر RU–X في حقل نفط الرميلة، وتحديداً تكوين الزبير. تمت مقارنة هذه الخصائص المقدرة بالقياسات المباشرة التي تم الحصول عليها من الاختبارات الميكانيكية ثلاثية المحاور وحيدة المحور التي أجريت على البئر RU–X، على التوالي. أظهرت النتائج وجود تشابه كبير بين التقديرات غير المباشرة والقياسات المباشرة، مما يدل على موثوقيتها في تحليل إنتاج الرمال ومساهمتها القيمة في بناء النموذج الجيوميكانيكي. علاوة على ذلك، تم التحقق من صحة نسبة بواسون الثابت باستخدام نتائج الاختبار الأساسية للمختبر، مما يدل على اتفاق معقول. من الجدير بالذكر أن التحقق من نسبة بويزن الساكن في تشكيل الزبير / الصخر الزيتي تضمن مقارنة القياسات المشتقة من المختبر مع القياسات الميدانية الفعلية. يمكن أن تُعزى اعلى قيمة لنسبة بويزن التي لوحظت في الصخر الزيتي إلى الانتشار البطيء للموجات الصوتية، وكانت نسبة الصحة في النتيجة $R^2 = 0.77$. بينما يشيراقل قيمة لمعامل يونج في التكوينات الشيل إلى مقاومة أقل للتشوه، مع نسبة الصحة في مقارنة النتائج $R^2 = 0.96$. توفر القياسات الساكنة، التي تأخذ في الاعتبار العوامل المؤثرة المختلفة، تمثيلًا أكثر واقعية لسلوك الصخور في ظل ظروف مختلفة. بالنسبة لمقاومة الانضغاط غير المحصورة ، كانت نسبة صحة المقارنة النسبية $R^2 = 0.83$.

الكلمات الدالة: حقل الرميلة النفطي، طبقة الزبير، نسبة بويزن، مجس اشعة كاما.