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Estimation of static modulus of carbonate formation for Rumaila oil field

Doaa Saleh Mahdi [a, b, *], Ayad A.Alhaleem A.Alrazzaq [a], Modhar Khan [c, d]

a Department of Petroleum Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
b Oil and Gas Engineering Department, University of Technology-Iraq, Baghdad, Iraq
c SLB,Dubai, UAE
d New York University, New York, United States

Abstract

Elastic parameters are essential for understanding the behavior of materials under stress, including their tendency for deformation and failure. Elastic modulus is a key parameter, which can be determined using static and dynamic methods. Dynamic methods involve analyzing properties from well logging such as density and wave velocity (compressional and shear waves), while static techniques quantify properties in a laboratory setting. While static techniques are the most accurate, they are also expensive and time consuming. However, there are correlations available to estimate static modules from dynamic modules, although many are specific to certain formations and not applicable to different rock types. In this paper, a new correlation was developed for predicting the static Young's modulus for carbonate formations in the Rumaila Oil Field based on dynamic modulus. Data from 4803 points in an 8.5 in hole size section between 1980 m and 2711 m depth were collected. The results showed that the new correlation accurately predicted the static Young's modulus of carbonate formation, a correlation coefficient (RSQ) of 97%, and an average absolute error of 8.15%. The new correlation provides a continuous profile of static Young's modulus with depth and ultimately leads to reduce the cost of estimating elastic properties in carbonate formations in the Rumaila Oil Field.

Keywords: Static Modulus; Elastic properties; well logging; Carbonate Formation.

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1- Introduction

Understanding the rock mechanical properties of formations is essential and plays a vital role in efficiently managing drilling and production operations to ensure the successful development and exploration of the well [1-4]. The major components of rock mechanical properties are the strength and elastic rock parameters. Elastic characteristics describe the material's behavior, including its susceptibility to deformation and failure under applied stress of a specific magnitude [5, 6]. Precisely determining the elastic properties of the rock is essential to prevent significant issues during well drilling, such as wellbore instability, kicks, differential sticking and others. Consequently, it is reasonable to obtain a reliable estimation of the elastic properties of rocks to ensure the success of well operations and can significantly enhance the economic income that can be obtained from the reservoir.

Among the most frequently utilized elastic properties is the young modulus (E), which represents the ratio of stress (σ) to strain (ε). There are two generally employed techniques for measuring the elastic modulus of rock material: static and dynamic. Static techniques measure the static properties in a lab by collecting core samples and performing laboratory experiments with simulating reservoir conditions, whereas dynamic (indirect) methods determine the dynamic properties from well logging such as the compressional wave velocities and the density log [7-10]. The mechanical tests are the most accurate predictor of the behavior of the rock's actual strength. However, because these techniques rely on using core samples and only reflect the properties of the rock at that particular location, they are expensive and time-consuming [11-13]. Due to the impact of several factors (e.g. fluid saturation, temperature, heterogeneity, lithology, isotropy, stress-strain, pore pressure, pore sand cracks, cement type, bedding planes, porosity, and rock microstructure) static measurements, static and dynamic methods frequently yield different elastic parameter values [14-17]. Static and dynamic conversion factors differ in different regions. The ratio of dynamic to static moduli was determined to be between 1 and 20 [18]. Stiff rocks have low ratios, while softer sediments have greater ratios. Ide [19] observed that the dynamic moduli of rock differs from the static due to the assumption made in deriving the relations for dynamic moduli. These relations assume that rocks are homogenous, isotropic, and completely elastic. Nevertheless, the majority of rocks are unable to meet such a requirement. Ide further stated that the dynamic moduli values were greater than the static

*Corresponding Author: Email: 150082@uotechnology.edu.iq

moduli values for the fine-grained, igneous rock. Tuman and Alm [20] conducted measurements of the dynamic and static Young's modulus of sandstone samples that were saturated. Their investigations demonstrated that the dynamic Young's modulus was greater than the static Young's modulus.

In his research, King [21] investigated the influence of anisotropy and nonlinearity on the mechanical characteristics of rocks. He discovered that the presence of randomly aligned lenticular cracks led to higher dynamic elastic moduli in comparison to static elastic moduli. Lin and Houze [22] conducted a comparison between the dynamic moduli obtained from well logs and acoustic measurements in a laboratory setting, with the static moduli determined in a laboratory. The results indicated a lack of consensus among the three groups of data. The disparities suggested the necessity for additional research to ascertain the underlying factors. Rabe and Odreman [23] demonstrated the use of ultrasonic triaxial tests conducted at high temperatures to replicate the effects of a steam aided gravity drainage (SAGD) operation on the rock characteristics of a heavy oil reserve in Venezuela. The purpose of the test was to assess how changes in temperature affect compressional velocity, which can be used to estimate the strength of rocks throughout SAGD processes. The results showed that the compressional velocity decreased by about twenty percent at a temperature of 1500 °C. Holt et al. [24] conducted an experiment to quantify the dynamic and static moduli of shales found in overburden. Their investigations demonstrated that the variation in strain amplitude and the dependency on frequency are the main factors causing differences between the static and dynamic moduli. Bretons et al. [25] examined the static and dynamic moduli of a calcarenite rock that was subjected to varying temperatures. They suggested two analytical formulas to describe the link between the static and dynamic modulus of this stone. The results were compared with relationships suggested by several researchers for various kinds of rocks. Rocks that have low elastic moduli typically indicate that they are extensively fractured. It was found that the static modulus is greatly influenced by the size, direction, and spatial distribution of cracks.

Several correlations that arise from the principles of elasticity and the physical interpretations of the constants are utilized to adjust the dynamic elastic modulus to obtain the static modulus across the whole depth of the reservoir sector, even in areas where core samples have not been collected but each of those equations only applies to particular kinds of rock within specific conditions. Canady [26] proposed a non-linear function for representing the adjustment of elastic moduli. Thus, it is crucial to conduct laboratory experiments on core samples in order to determine the correlation between dynamic and static elastic parameters under reservoir conditions.

In this study, a new correlation is developed to determine the static Young's modulus from well log data (i.e. dynamic modulus) for carbonate formation in the Rumaila oil field.

2- Methodology

This study presented a new equation for determining the static Young's modulus from the dynamic Young's modulus. Firstly, sonic logging and bulk density log are used for estimating the dynamic modulus. The formula proposed by Goodman [27] is used to calculate the dynamic Young's modulus (E):

$$E_{dyn} = \rho v_s^2 \left(\frac{3v_p^2 - 4v_s^2}{v_p^2 - v_s^2}\right) \quad (1)$$

Where: E_{dyn}: dynamic Young's modulus, ρ: bulk density, Vp compressional wave velocity, and Vs: shear waves velocity.

It is well known that the dynamic modulus derived from the previous formula contains overestimated values and must be transformed into a static modulus that is appropriate for this specific region. Empirical relationships produced using data collected at the laboratory scale are used to achieve this. As a result, a continuous profile of the static modulus within the reservoir's depth is produced by comparing the dynamic modulus derived from the log data with the static modulus observed through laboratory experimentation at specific depth points. This process is crucial for producing a trustworthy profile of static modulus. There are a number of correlations that can be used to obtain the static modulus for the entire depth range. These correlations are often insufficient to explain the behavior of other rock samples since they are based on particular lithologies. Thus, building a relationship that explains a certain behavior for a particular type of rock is essential. Background information on empirical relationships for estimating static modules from dynamic modulus in carbonate formation is presented in Table 1.

Table 1. Previous correlations for static modulus prediction in carbonate formation

Equation No.	Static Modulus Equation	Reference
(2)	$E_{st} = 0.74E_{dyn} - 0.82$	Eissa and Kazi [28]
(3)	$E_{st} = 0.018\, E_{dyn}^{\ 2} + 0.422E_{dyn}$	Lacy [29]
(4)	$E_{st} = 1.153\, E_{dyn} - 15.2$	Nur and Wang [30]
(5)	$E_{st} = 0.867E_{dyn} - 2.085$	Brotons et al. [25]
(6)	$E_{st} = 0.014E_{dyn}^{\ 1.96}$	Najibi et al. [31]

Fig. 1 shows the cross plot of the dynamic Young's modulus (E_{dyn}), obtained from log data, and the static Young's modulus (E_{st}), determined from laboratory experiments on 16 core samples taken from carbonate formation in the drilled wells. The accuracy of previous correlations predicting the static modulus for carbonate formation in the Rumaila oil field has been assessed. A total of 4803 well log data points were obtained from an 8.5 in hole size section of an oil well in the Rumaila oil field's carbonate formations (i.e. Sadi, Khasib, Mishrif, Rumaila, Ahmadi, and Mauddud) with a thin barrier of shale formation (i.e. Tanuma) within a depth range of 1980 m to 2711 m. Gamma ray, bulk density, compressional, and shear wave velocities logs were recorded as a function of depth for all 4803 data points, and the associated dynamic modulus was calculated using Eq.1.

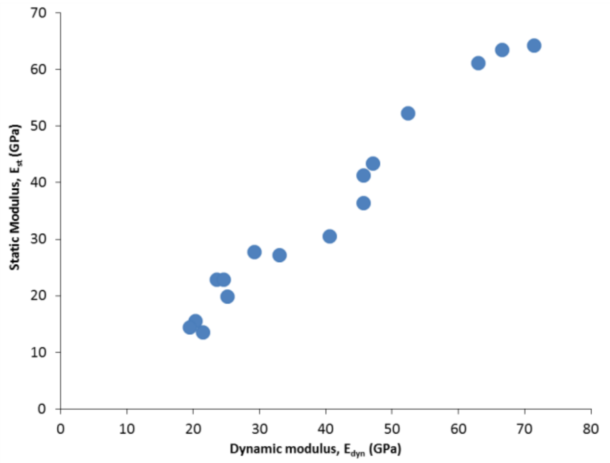

Fig. 1. Measured static modulus with well log dynamic modulus for the investigated formation

3- Results and discussion

A new relationship is created using the measured static modulus and the corresponding dynamic modulus from the well log to estimate the static modulus from the dynamic modulus for carbonate formations. The findings indicate that the following equation (Eq. 7) is the best form for the correlation between static modulus and dynamic modulus:

$$E_{st} = 1.0019\, E_{dyn} - 4.6401 \quad (7)$$

Where E_{st} is the static Modulus (GPa), and E_{dyn} is the Dynamic Modulus (GPa).

Table 2 lists the variable ranges for the new correlation (Eq. 7) that were utilized. The new relationship can precisely predict the friction angle and has a correlation coefficient (RSQ) of 0.9714 (Fig. 2).

Table 2. Statistical analysis of the core and well log data from the carbonate formation

Property	Minimum	Maximum	Mean
Gamma Ray (gAPI)	20.91	132.96	53.22
Edyn (GPa)	10.24	67.38	34.77
RHOZ (g/cm^3)	1.82	2.73	2.50
DTCO (us/ft)	41.98	146.66	72.06
DTSM (us/ft)	96.69	185.22	135.75

The cross-plots of the computed static modulus from the former correlations (Eqs 2 to 6) and the new correlation (Eq. 7) are displayed in Fig. 3. The relation between E_{dyn} and Est in the samples under study is depicted in Fig. 3. The ideal connection (i.e. Edyn = Est) is represented by the straight line (line with slope equal to 1). It is evident from Fig. 3 that the previously suggested relations do not work well for estimating Est from Edyn to the current data. In addition, the new correlation performs better than published correlations in calculating the static modulus for carbonate formations. According to the findings (Fig. 4), the new correlation has the lowest average absolute error (AAER).

Therefore, we conclude that the newly proposed correlation (Eq. 7) is the most reliable method for accurately predicting the static modulus of carbonate formation in the Rumaila Oil Field. The results of this study demonstrate that the new empirical equation, which connects petrophysical logs and rock mechanical characteristics, can be effectively applied in scenarios where core data is not easily accessible.

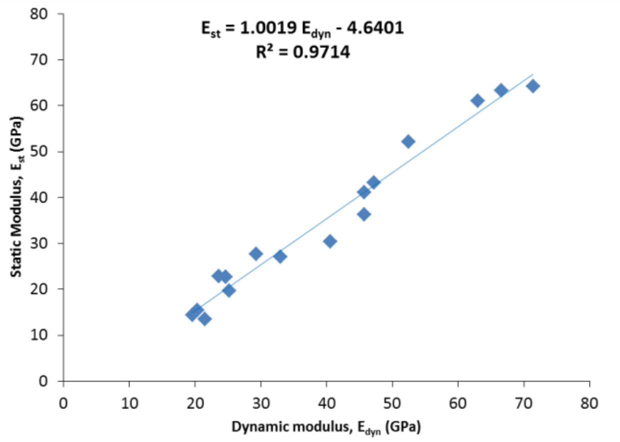

Fig. 2. The new correlation for carbonate static modulus prediction from dynamic modulus

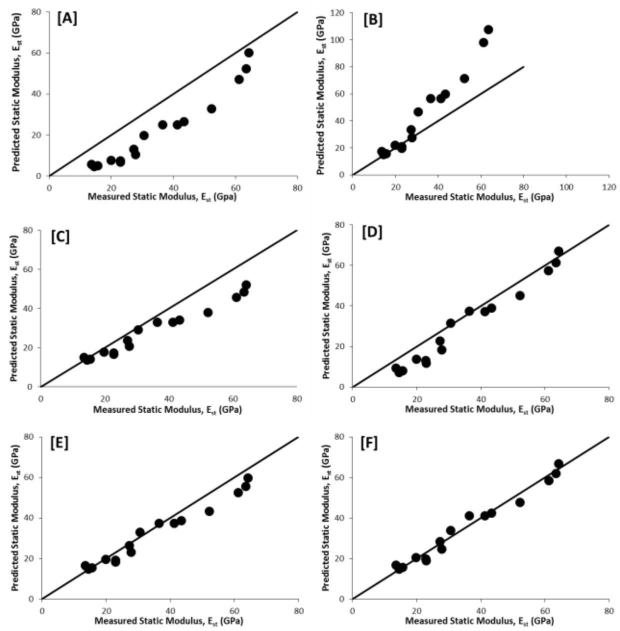

Fig. 3. Comparison of the cross-plots of the predicted versus measured static modulus of carbonate formations for the previous and the newly developed correlation. Where: A (Eq. 2; Eissa and Kazi), B (Eq. 3; Lacy), C (Eq. 4; Nur and Wang), D (Eq. 5; Brotons et al.), E (Eq. 6; Najibi et al.), and F (Eq. 7; Current study)

Finally, using the new correlation (Eq. 7), a continuous static modulus profile is created for the depth range (1920 m to 2711 m) for the carbonate formation of the Rumaila oil field (Fig. 5). It is to be noted that locations with strong formation stability and peak values are reached. The elastic characteristics of the rock will often increase with greater sonic velocity, which corresponds to increasing density. In comparison to the dynamic modulus, the static modulus profile creates an image in which the static modulus varies along with the dynamic modulus.

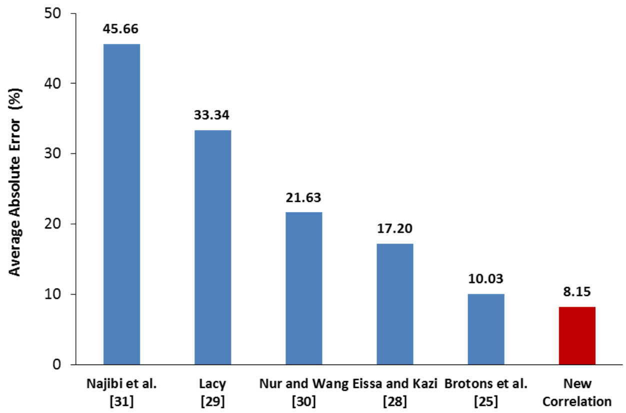

Fig. 4. Accuracy of the previous and current study correlations to predict static modulus

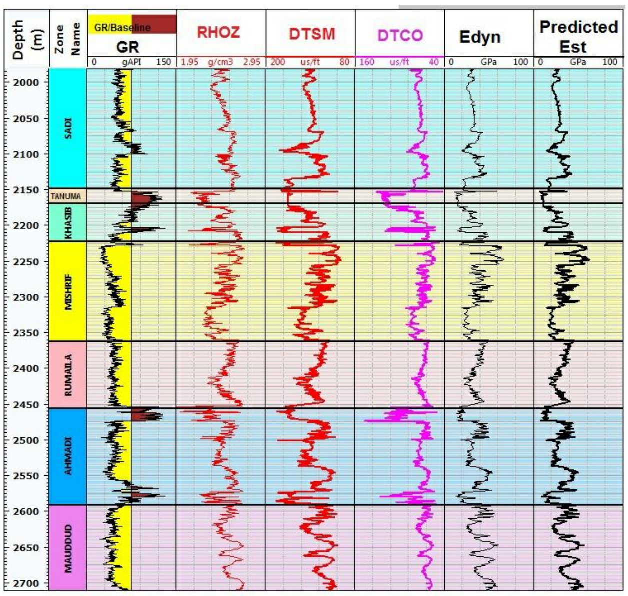

Fig. 5. The computed static modulus profile for carbonate formation from the new correlation with the well log data and the associated dynamic modulus

4- Conclusion

Elastic properties refer to how a material responds to stress, including its propensity to deform and fail when subjected to applied stress. One key parameter, elastic modulus, can be calculated through both static and dynamic methods. Static techniques measure the static properties in the laboratory, while dynamic techniques use data from well logging. Although static methods are considered as the most accurate way to measure elastic modulus, they are also the most expensive and time-consuming. The estimation of the static modulus from the dynamic modulus has been proposed using a variety of correlations. Most of these correlations were often specific for particular formations and thus they are not applicable. To predict the static Young's modulus for carbonate formations of an Iraqi oil field as a function of dynamic modulus, we therefore developed a new correlation in this paper. Data were collected from specific sections of the well, a total of 4803 data points. The findings demonstrate that the new correlation has the highest accuracy for predicting the static Young's modulus in the carbonate formation of the Rumaila oil field; with a correlation coefficient (RSQ) of 0.97% and an average absolute error of 8.15%. However, the average absolute error of the other correlations in literature is determined to be 45.66%, 33.34%, 21.63%, 17.20 %, and 10.0 % for Najibi et al., Lacy, Nur and Wang, Eissa and Kazi, and Brotons et al. correlations, respectively. The new correlation enables continuous depth profiles for static young's modulus and lowers the cost of estimating elastic properties for carbonate formation.

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تقدير معامل يونغ الساكن لتكوين الكربونات في حقل الرميلة النفطي

دعاء صالح مهدي [١، ٢، *]، اياد عبد الحليم عبد الرزاق [١]، مظهر خان [٣، ٤]

١ قسم هندسة النفط، كلية الهندسة، جامعة بغداد، بغداد، العراق
٢ قسم هندسة النفط و الغاز ، الجامعة التكنولوجية، بغداد، العراق
٣ SLB، دبي، الإمارات العربية المتحدة
٤ جامعة نيويورك، نيويورك، الولايات المتحدة

الخلاصة

تميز معلمات المورنة سلوك المادة مثل ميلها للتشوه والفشل عند تعرضها لأجهاد مسلط على حجم معين. معامل المورنة هو أحد هذه المعلمات، والتي يمكن تحديدها باستخدام طرق ساكنة وديناميكية. في حين أن الطرق الديناميكية تحسب الخصائص الديناميكية من تسجيل الآبار بما في ذلك الكثافة وسرعات موجات الضغط والقص، فإن التقنيات الساكنة تحدد الخصائص الساكنة في المختبر. تعتبر التقنيات الساكنة هي الطريقة الأكثر دقة للحصول على معامل المرونة ولكن هذه الطريقة مكلفة وتستغرق وقتا طويلا. على الرغم من ذلك، هناك العديد من العلاقات التي تم اقتراحها لتقدير معامل يونغ الساكن من المعامل الديناميكي. تم تصميم غالبية هذه العلاقات لتكوينات محددة، لذا لا يمكن استخدامها لأنواع مختلفة من الصخور. وهكذا، في هذا البحث، قمنا بتطوير علاقة جديدة للتنبؤ بمعامل يونغ الساكن لكربونات حقل النفط العراقي كدالة للمعامل الديناميكي. تم جمع ٤٨٠٣ نقطة بيانات من مقطع من بئر وبقطر ٨,٥ بوصة مع فاصل عمق يتراوح بين ١٩٨٠ مترًا و ٢٧١١ مترًا. أظهرت النتائج أن العلاقة الجديد قادر على التنبؤ بمعامل يونغ الساكن للكربونات بدقة عالية (أي أن معامل الارتباط (RSQ) للعلاقة الجديد كان ٩٧% ومتوسط الخطأ المطلق ٨,١٥%). تساعد العلاقة الجديدة في توفير قراءة مستمرة لمعامل يونغ الساكن مع عمق البئر ويؤدي إلى تقليل تكلفة تقدير الخواص المرنة لتكوين الكربونات.

الكلمات الدالة: المعامل الساكن، الخواص المرنة، تسجيل الآبار، تكوين الكربونات.