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Prediction of shear wave velocity in three sedimentary rocks in East Baghdad oilfield using multiple regression analysis

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Abstract

Shear wave is a crucial parameter for assessing the wellbore stability, the stress response, and rock deformation. It is essential for constructing the mechanical earth model (MEM) for many applications related to reservoir geomechanics including wellbore stability, sand production, hydraulic fracturing, and fault reactivation. However, shear sonic data is often omitted during the well-logging measurements for cost and saving purposes. To overcome this challenge, recent research has been focused on determining shear wave velocity through the use of core plugs, empirical correlations, artificial intelligence techniques, and multiple regression to quantify and evaluate the mechanical properties of subsurface formations without performing direct measurements at the wellbore. The greatest difference between this study and the literature is to predict the shear wave velocities for three sedimentary rocks based on conventional well logs.

This study has been conducted on datasets of two wells drilled in the East Baghdad oilfield, for which there is a lack of shear wave data. Two formations (Tanuma and Zubair formations) within the production section of this field were conducted to develop new models for determining the shear wave velocity using multiple regression analysis. These two formations primarily consist of three lithologies: limestone, sandstone, and shale. Before the model development, data analysis on the selected data was applied to figure the most influential parameter(s) in determining the shear wave velocity. The results of the developed models are then compared with the previous models in the literature.

The results showed that the multiple regression analysis technique is a powerful technique in determining shear wave velocity with high-performance capacity. The correlation coefficient (R^2) and the root mean square error (RMSE) were 0.84 and 0.092 for limestone, 0.84 and 0.0972 for sandstone, and 0.86 and 0.0796 for shale respectively. Furthermore, the performance of the developed models is well matched to the actual shear wave data rather than the Castagna correlations. The findings of this study are effective in determining shear wave velocity for future applications related to reservoir geomechanics without needing costly well-log or core measurements.

Keywords: shear wave velocity; multiple regression analysis; compressional wave velocity; sandstone, limestone; and shale.

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1- Introduction

Determining shear wave and compressional wave velocities is crucial in constructing the mechanical earth model (MEM) for the field of interest, as these measurements are crucial for determining the elastic features of rocks. Analyzing the wellbore instability problems and predicting the sand production requires knowledge of the elastic rock properties [1]. Drilling and wellbore stability hazards can be mitigated by using optimum mud weights based on the elastic and mechanical rock properties that are combined with formation pore pressure and in-situ stresses [2]. Such elastic rock properties are Young's modulus, Poisson's ratio, the shear modulus, the rock compressibility factor, and Biot's coefficient. Thus, shear and compressional wave velocities play a pivotal role in characterizing the mechanical properties and behavior of subsurface formations, providing valuable insights into the stiffness, elasticity, and shear wave transmission capabilities of rocks [3-4]. By analyzing the shear wave velocity, we can effectively assess the stability of rock formations and their response to stress and deformation, thereby enabling the prediction and mitigation of potential geomechanical challenges, such as wellbore stability, sand production, and induced seismicity [5]. Shear wave data can aid in designing mud programs, casing plans, and wellbore stability analysis, ensuring the appropriate selection of drilling parameters and mitigating drilling risks. Shear wave velocity (Vs) is a crucial parameter in petrophysical rock evaluation, as it can be used to estimate the rock's mechanical properties based on compressional-wave velocity and bulk density [6]. However, shear sonic data is often omitted during well logging for cost and time-saving purposes.

Empirical correlations have been developed in the literature to determine the shear wave velocity of rocks using different techniques such as multiple regression analysis and neural network methods. This development is to overcome the lack of shear wave data for any field of

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interest. The comprehensive equation was developed using statistical techniques tailored to carbonate rocks [7]. Naji et al. [8] utilized an artificial neural network to predict shear wave velocity for directional oil wells in Iraq's Fauqi oilfield. They developed a high-performance mathematical model using 1922 data points to determine the shear wave velocities. Bashara and Hadi [9] used artificial neural networks (ANNs) to fill the gaps in shear wave data in the southern and northern domes of the Rumaila oilfield. The model's efficacy was measured via calibration, revealing critical elements like depth, bulk density, and compressional velocity. This method offers a cost-effective alternative to the costly rock tests and DTs measurements.

Shear and compressional wave datasets are typically absent or insufficient in any interesting field, especially at shallow depths [10]. Shear wave data is also required for making credible computations [11-12]. Elastic rock mechanics properties such as Young’s modulus, Poisson’s ratio, Biot's coefficient, shear modulus, and rock compressibility factor can be calculated using sonic waves and density as key parameters [13]. Compressional and shear wave velocities are the most crucial factors in determining the mechanical properties of rocks [14]. The high cost of coring operations often limits their use in oil and gas field wells, making it difficult for researchers to access crucial data. To overcome this challenge, numerous empirical correlations have been developed based on petrophysical survey data [15]. Assessing shear wave velocity (Vs) is a crucial element in designing drilling operations. Reservoir geomechanics plays a vital role in drilling engineering, as it provides comprehensive insights into the mechanical behavior of rocks under subsurface stress and forecasts their potential movement [16]. Rock mechanics properties are better determined using shear wave logs than from direct core measurements due to limitations in core sample availability, time, and expenditures [17].

This study aims to develop new models for estimating shear wave velocity within three distinct sedimentary rock formations: limestone, sandstone, and shale (Tanuma and Zubair formations) within the production section of the East Baghdad oilfield. The application of multiple regression analysis techniques and comparing the results with Castagna correlations were also performed in this study.

1.1. Area of study

East Baghdad oilfield (EB oilfield) constitutes one of the most important large fields in Iraq. It is about 120 kilometers by 10 kilometers and is extended northwest-southeast, with its major component in northern Baghdad. The field is composed of several formations, including three major formations: Tanuma, Khasib, and Zubair. Based on the final well report, oil and gas production commenced from these three formations in January 1980. The discovery of this field dates back to 1974 when the Iraq National Oil Company (INOC) identified its presence in the Al-Swairah area (Southeast) extending up to AL-Nibayia (northwest) [18], as depicted in Fig. 1.

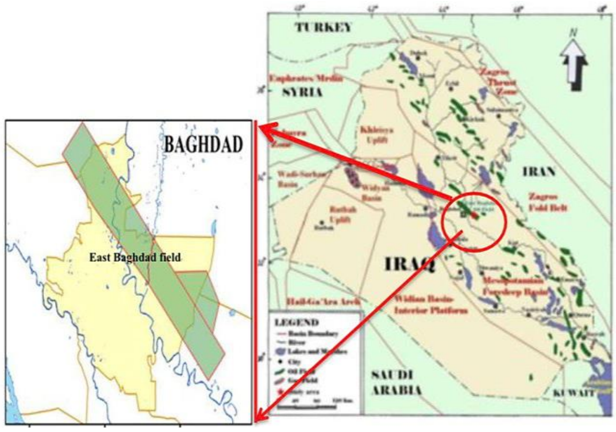

Fig. 1. Location of East Baghdad Oilfield [19]

1.2. Geology of field study

East Baghdad oilfield is located in the fore deep geological province in northern Mesopotamia. The generalized stratigraphy of the Cretaceous to Tertiary, as defined by the Iraqi National Oil Company (INOC), comprises three lithological subdivisions:

- Cretaceous: mostly limestone with dolomite, sandstone with shale, marl, and evaporite;
- Paleocene to Oligocene: limestone, marl, and evaporite;
- Miocene to Pleistocene: sandstone with shale, limestone, and evaporite.

Cretaceous limestone and sandstone reservoirs are the most prolific oil interval in Iraq and western Iran. In southern and central Iraq, the Cretaceous shows a cyclic pattern of sedimentation characterized by an alternation of porous permeable limestone or sandstone reservoirs, and impermeable intra-shale or limestone cap rocks. Thick marly limestone, marl, and shale with good source rock potential were deposited in eastern Iraq and western Iran during the early to center Cretaceous [19]. Fig. 2 shows the stratigraphic column of East Baghdad oilfield which extends from Ingana to Adaiyah formation. According to Al-Ameri and AlObaydi [20], geological deposits spanning from the Jurassic to the Pliocene periods consist of a variety of rocks, including carbonate shale, anhydrite, marl, sandstone, and siltstone.

2- Methodology

Multiple regression analysis is presented in this study to develop a new correlation for forecasting shear wave velocities based on conventional well log data in the East Baghdad oilfield. Tanuma and Zubair formations are two of the most notable reservoirs in the East Baghdad oilfield. The results will be then compared with the empirical equations developed by Castagna although regression can also be applied to experimentally acquired variables; it is most commonly used for naturally occurring variables (parameters) [20].

Statistically speaking, multiple regression analysis is used when numerous independent variables are used to predict a single dependent variable. It has widespread application, particularly in scientific study and statistical analysis. Criteria for choosing the independent variables in a multiple regression model have been established in prior research. Each new area or field may, however, require a different collection of independent variables and a separate prediction equation. This emphasizes the significance of giving multiple regression analysis due consideration and tailoring it to specific settings. Better predictions can be made in a certain area or discipline by refining the regression model through the selection of relevant independent variables and the creation of targeted prediction equations.

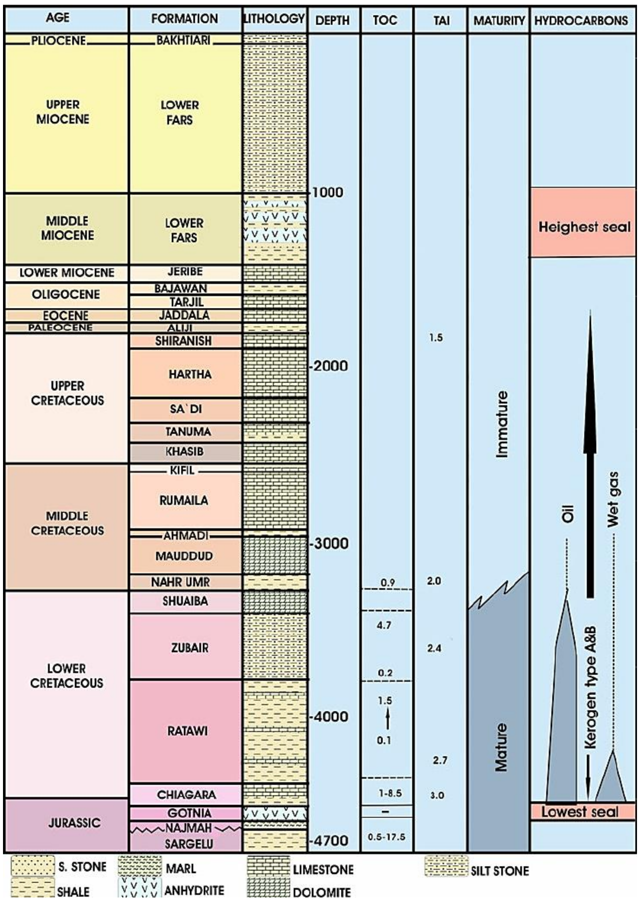

Fig. 2. Geological sequence of East Baghdad Oilfield [19]

3- Review of shear wave estimation

Knowing the shear wave velocity (Vs) is a key parameter in determining the mechanical rock properties and the stability of underground formations. In oil and gas exploration, seismic data interpretation, and geotechnical engineering, just to name a few fields, an accurate assessment of Vs is crucial. This article summarises the various techniques used to estimate shear wave velocity, including their advantages, disadvantages, and geophysical applications.

Multiple regression analysis is one of the most extensively used predictive techniques [21] for identifying correlations between rocks' mechanical features and other factors. Several researchers, including Castagna [22], Eskandari [23], Brocher [24], Ameen [11], and Al-Kattan [7], have produced good empirical correlations for predicting shear wave velocities. Factual forecasts are only as good as the quantity and ease of available data allow for. Another potential gain is using these forecasts in long-term strategic planning.

Developing empirical correlations between Vs and other geophysical parameters is a typical method; for example, the Castagna equations [22] give such empirical relationships. Sandstone, limestone, shale, and dolomite are only a few examples of the types of rocks for which there are established relationships. Shear wave velocity (Vs) in various rocks such as shale, limestone, and sandstone can be estimated using the Castagna correlation, which is an empirical equation. The connection between the two velocities, Vs and Vp, is established via the correlation. Vs and Vp are input parameters in the equation developed by Castagna [22], in kilometers per second. The correlation equation provides different constants for different types of rocks, enabling more precise predictions to be made for sandstone, limestone, shale, and dolomite. Shale, limestone, and sandstone shear wave velocities can be estimated from compressional wave velocities using the Castagna correlation. To evaluate the validity of the correlation, it is necessary to compare the estimated values to measure shear wave velocities. The correlation coefficient and percentage of error are commonly used metrics to evaluate the precision of the Castagna correlation in estimating a shear wave velocity for different rock types. The specific equations proposed by Castagna [22], for estimating shear wave velocity (Vs) in different rock types based on compressional wave are shown in Table 1.

Table 1. Castagna correlations to estimating shear wave velocity (Vs) for different rock types [22]

Relationship of shear wave velocity (km/sec)	Type Lithology	Equation No.
$Vs = -0.055 * Vp2 + 1.017 * Vp - 1.031$	Limestone	(1)
$Vs = 0.862 * Vp - 1.172$	Shale	(2)
$Vs = 0.804 * Vp - 0.856$	Sandstone	(3)
$Vs = 0.583 * Vp - 0.0776$	Dolomite	(4)

4- Results and discussion

This section presents the results of the developed models for determining the shear wave velocities in three sedimentary rocks which are limestone, sandstone, and shale. The performance capacity of the presented models was determined based on two criteria, determination coefficient (R^2) and root mean square error (RMSE). The results are then compared with the Castagna correlations.

4.1. Model development

Well-log data has been prepared and verified for one of the wells drilled in the East Baghdad oilfield, the southern region of the same field (EBS). Where multiple regression analysis methods were used to predict the shear wave velocity for the area of study, including the Tanuma and Zubair formations, which consist of limestone, shale, and sandstone. A general model development has been established for each limestone, shale, and sandstone to predict the shear wave velocity with the best correlation coefficient, close to one, and the lowest root mean square error RMSE for each rock formation, the equations have one input parameter (Vp Km/sec) with the depth(m).

The obtained results from the relationship between the predicted and the actual shear wave velocity showed a realistic correlation coefficient close to one. Based on the multiple regression analysis techniques applied to the studied wellbore. This relationship was illustrated in Figures 3 to 5, where equations 5, 6, and 7 were developed for limestone, shale, and sandstone, respectively, which are shown in Table 2.

Notably, the correlation coefficients for the developed models were found to be 0.84, 0.86, and 0.84 for limestone, shale, and sandstone, respectively.

Table 2. Models development to predict shear wave velocity for different lithology types

Relationship of shear wave velocity (km/sec)	Type Lithology	Equation No.
$Vs = -3.57 + 0.397 * Vp\ km/sec + 0.0016 * TVD\ m$	Limestone	(5)
$Vs = 7.3597 + 0.6409 * Vp\ km/sec + - 0.0033 * TVD\ m$	Shale	(6)
$Vs = -0.75 + 0.00033 * TVD\ m + 0.47 * Vp\ km/sec$	Sandstone	(7)

Where the transit time (DT, µs/f) measured by the sonic log is normally used to calculate the compressional wave velocity (Vp, Km/sec):

$$Vp = 1 * 10^6 * \frac{0.3048}{DT} * 1000, Km/sec \quad (8)$$

In Fig. 3 through Fig. 5, the expected and actual shear wave velocities are displayed against each other. The strong correlation coefficients (R^2) obtained for limestone, sandstone, and shale indicate that the selected input parameters, pressure wave velocity, and formation depth, are highly effective in predicting shear wave velocities for these sedimentary rocks. Additionally, the relatively low root mean square errors (RMSE) indicate the accuracy and reliability of the developed models, further supporting their practical utility.

The results of our research revealed promising outcomes in predicting shear wave velocities for the three sedimentary rocks using the multiple regression method. The models achieved favorable correlation coefficients (R^2) and root mean square errors (RMSE) when compared to the actual shear wave velocities .

For limestone, the multiple regression model yielded a correlation coefficient (R^2) of 0.84, indicating a strong linear relationship between the expected and actual velocities of shear waves. The corresponding root mean square error (RMSE) of 0.092 implies a relatively small average difference between the predicted and actual shear wave velocities for limestone, as shown in Fig. 4.

Similarly, the developed model for sandstone showed a correlation coefficient (R^2) of 0.84, suggesting a robust association between the expected and actual velocities of shear waves. The associated root mean square error (RMSE) of 0.0972 indicates a reasonably low average deviation between the predicted and measured values for sandstone, as Fig. 5 shows.

Moreover, the model for shale exhibited a correlation coefficient (R^2) of 0.86, indicating a strong correlation between the predicted and actual shear wave velocities. The corresponding root mean square error (RMSE) of 0.0796 signifies a relatively low average difference between the predicted and measured values for shale, as shown in Fig. 4.

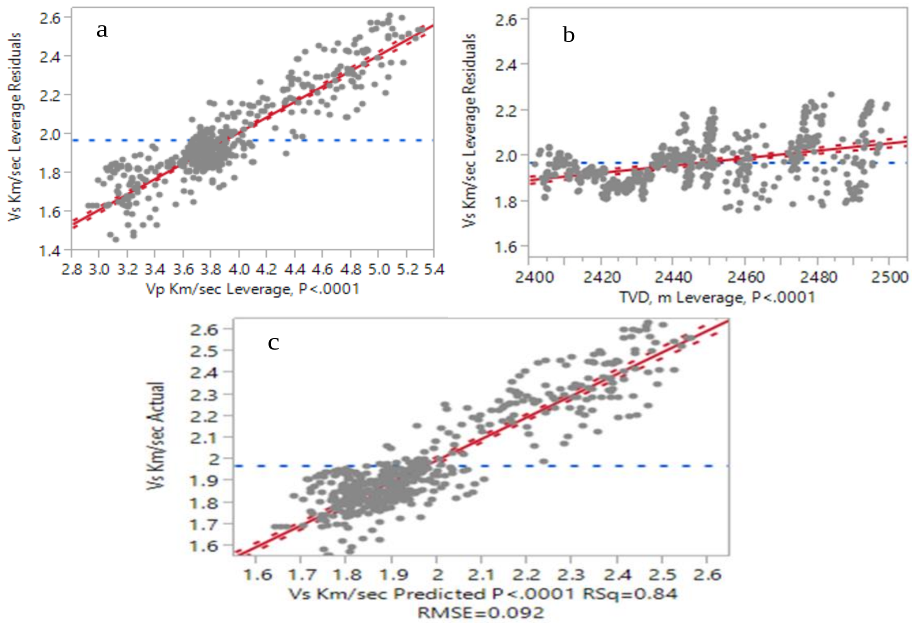

Fig. 3. Models Development for Estimating Shear Wave Velocity in Limestone: (a) Vs vs. Vp, (b) Vs vs. TVD, (c) Actual Vs vs. Predicted Vs

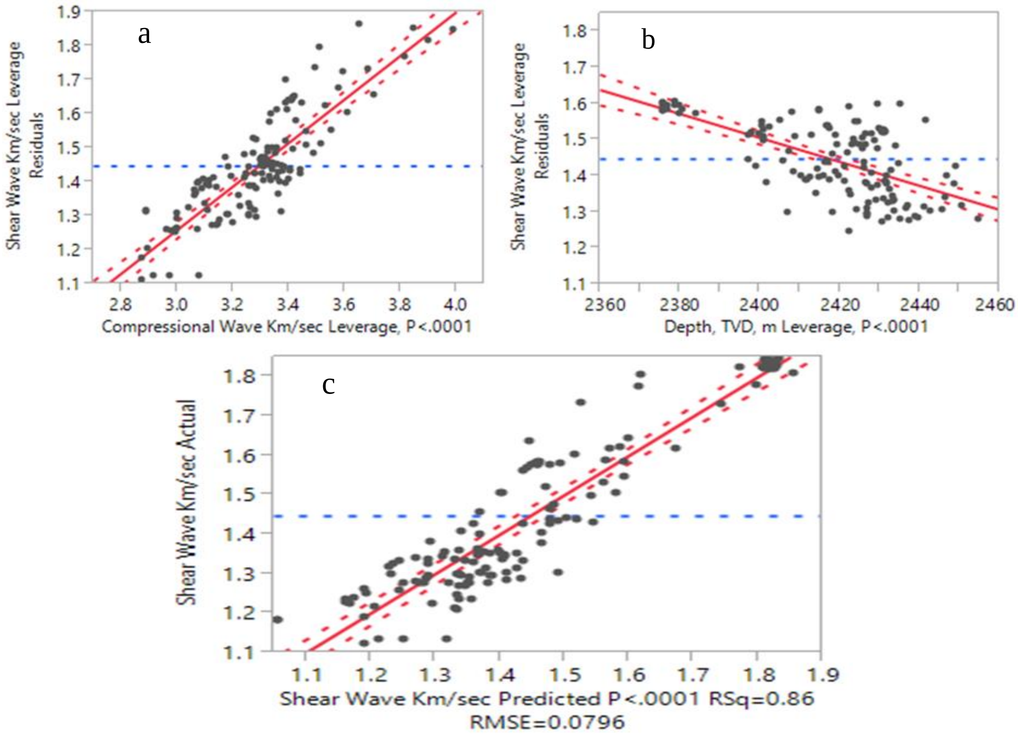

Fig. 4. Models Development for Estimating Shear Wave Velocity in Shale: (a) Vs vs. Vp, (b) Vs vs. TVD, (c) Actual Vs vs. Predicted Vs

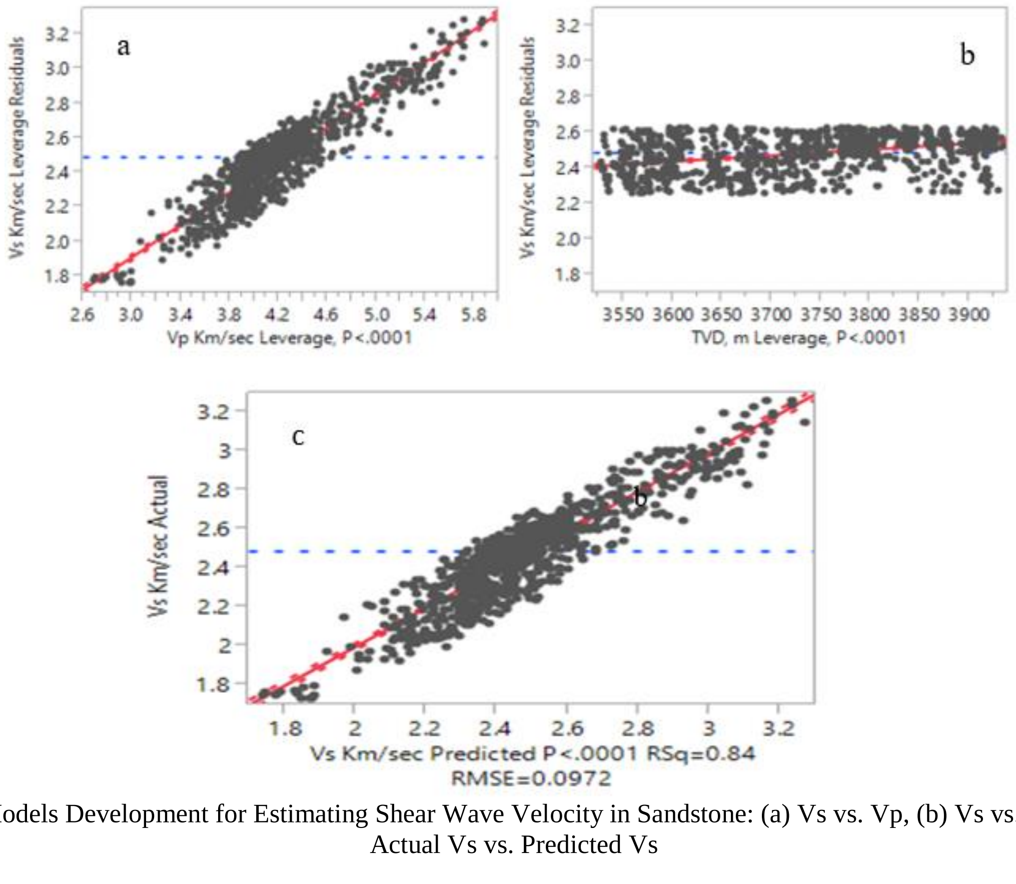

Fig. 5. Models Development for Estimating Shear Wave Velocity in Sandstone: (a) Vs vs. Vp, (b) Vs vs. TVD, (c) Actual Vs vs. Predicted Vs

4.2. Comparison with castagna correlations

An important finding of this research was that the developed models showed better consistency with the actual shear wave velocities compared to the widely used Castagna correlations. This outcome suggests the potential superiority of the multiple regression approach in capturing the complexities and nuances of the relationships between the input parameters and shear wave velocities in these sedimentary rocks. This study's developed correlations can be considered a valuable tool for estimating shear wave velocity based on compressional wave velocity (Vp) in these formations (limestone, shale, and sandstone). Multiple regression models take into account additional factors and variables that may not be adequately considered by the Castagna correlations, resulting in improved accuracy.

The East Baghdad field data was used to build models, and these are compared to Castagna's proposed empirical equations. In the circumstances where castagna correlations were utilized to estimate shear wave velocity via Eqs. 1, 2, and 3, Fig. 6 through Fig. 8 show a comparison of the actual and predicted shear wave velocities.

Compared to the Castagna correlations, the created models perform better, suggesting that the multiple regression approach takes into account more features and variables, leading to a more precise prediction of shear wave velocities. The traditional correlations may overlook certain geological complexities or fail to capture the specific characteristics of the analyzed formations.

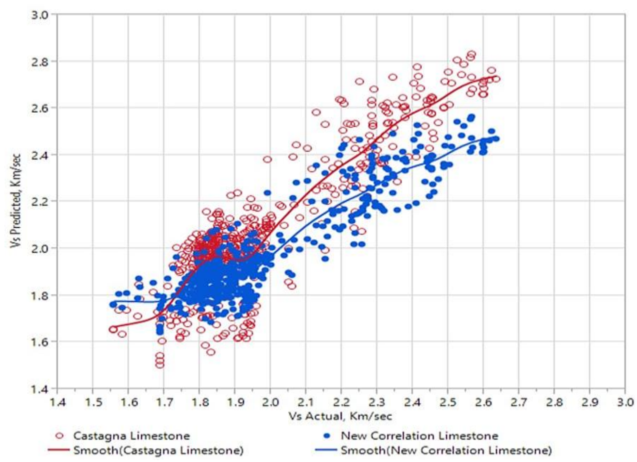

Fig. 6. Comparison of shear wave velocity in limestone between developed and Castagna Correlation

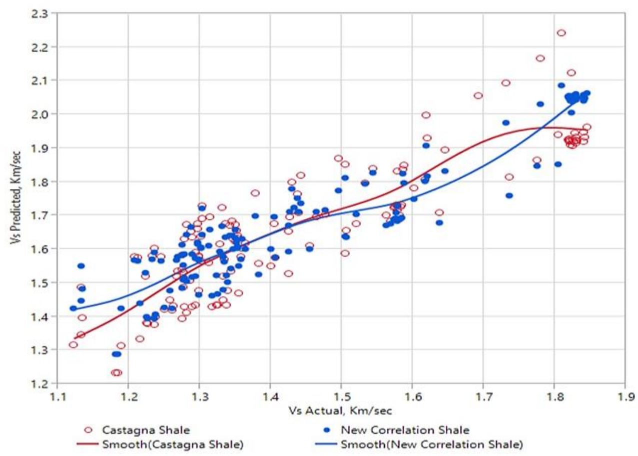

Fig. 7. Comparison of shear wave velocity in Shale between developed and Castagna Correlation

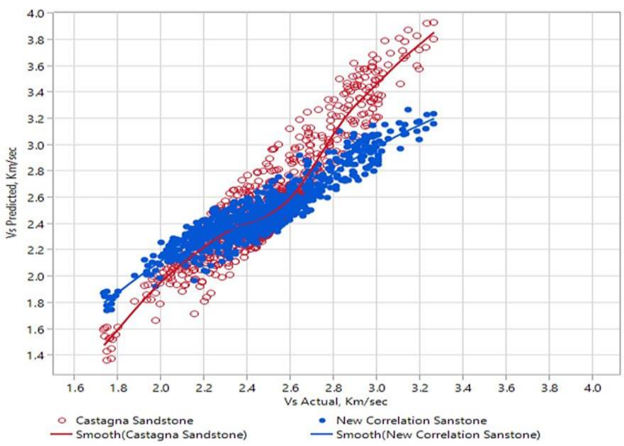

Fig. 8. Comparison of shear wave velocity in Sandstone between developed and Castagna Correlation

5- Conclusions

This study presents new models to determine the shear wave velocity based on conventional well logs in three sedimentary rocks which are limestone, sandstone, and shale. The findings of this research further strengthen the potential applicability and accuracy of the developed models in the East Baghdad oilfield.

An important finding of this research was that the developed models showed a better consistency with the actual shear wave velocities compared to the commonly used Castagna correlations. This outcome suggests the potential superiority of the multiple regression approach in capturing the complexities and nuances of the relationships between the input parameters and shear wave velocities in these sedimentary rocks. Thus, the multiple regression technique can be effectively adopted to foresee shear wave velocity and use it to construct a mechanical earth model (MEM), ensuring safe and efficient drilling operations .

The findings of this study can be used for future good planning in the East Baghdad oilfield that is related to reservoir geomechanics without the need for performing costly good log measurements or core lab measurements. It can also be used in other oil fields with the highly recommended calibration for increasing the accuracy of determining the elastic rock properties.

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التنبؤ بسرعة موجة القص في ثلاثة صخور رسوبية في حقل نفط شرق بغداد باستخدام تحليل الانحدار المتعدد

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الخلاصة

سرعة موجة القص هي اداة مهمة لتقييم استقرار البئر والاستجابة للضغط وتشوهات الصخور. إنها ضرورية لبناء نموذج الأرض الميكانيكية (MEM) ، لتنفيذ العديد من القضايا المتعلقة بجيولوجيا المكمن بما في ذلك استقرار البئر، إنتاج الرمال، التكسير الهيدروليكي، وإعادة تنشيط الصدع. غالبًا ما يتم حذف بيانات الموجات الصوتية القصية أثناء قياسات ال logging في البئر لأغراض التكلفة والتوفير. للتغلب على هذه التحدي، ركزت الأبحاث الحديثة على التنبؤ بسرعة موجة القص من خلال استخدام العمل التجريبي، والتباينات التجريبية، وتقنيات الذكاء الاصطناعي، والانحدار المتعدد لوصف وتقييم الخصائص الميكانيكية للتكوينات السطحية دون إجراء قياسات مباشرة في البئر. الهدف من هذه الدراسة هو التنبؤ بسرعة الموجة القصية بناءً على سجلات الآبار التقليدية بما في ذلك سرعة الموجة الضاغطة وبيانات عمق التكوين.

أجريت هذه الدراسة على مجموعات بيانات من بئرين في حقل نفط شرق بغداد. تم إجراء مجموعات بيانات من تكوينين (تكوينات تانوما وزبير) في قسم الإنتاج من هذا الحقل لتطوير نماذج جديدة لتحديد سرعات الموجات القصية باستخدام تحليل الانحدار المتعدد. تتكون هذه التكوينات في المقام الأول من ثلاثة وحدات جيولوجية: الحجر الجيري والرمل والطين. قبل تطوير النموذج ، تم تطبيق تحليل البيانات على البيانات المحددة لتحديد المعلمة الأكثر تأثيرًا على سرعة الموجة القصية. ثم يتم مقارنة نتائج النماذج المطورة مع النماذج السابقة التي تم تقديمها في الأدبيات.

أظهرت النتائج أن تقنية تحليل الانحدار المتعدد هي تقنية متحفظة في تحديد سرعة الموجة القصية بسعة أداء عالية. كانت معامل الارتباط (R^2) وخطأ الجذر المتوسط المربع 0.84 (RMSE) و ٠,٠٩٢ للحجر الجيري، و ٠,٨٤ و ٠,٠٩٧٢ للرمل ، و ٠,٨٦ و ٠,٠٧٩٦ للطين على التوالي. ولذلك، فإن نتائج النماذج المطورة تتطابق بشكل متسق مع بيانات موجة القص الفعلية بدلاً من معادلات Castagna .إن النتائج التي توصلت إليها هذه الدراسة فعالة من حيث التكلفة في تحديد سرعة الموجة القصية للتطبيقات المستقبلية المتعلقة بجيولوجيا المكمن دون الحاجة إلى قياسات سجلات الآبار أو core باهظة الثمن.

الكلمات الدالة: سرعة موجة القص، تحليل الانحدار المتعدد، سرعة موجة الانضغاطية، الرمل، الحجر الجيري والطين وصخرة الشيل.