A Predictive Model for Estimating Unconfined Compressive Strength from Petrophysical Properties in the Buzurgan Oilfield, Khasib Formation, Using Log Data

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Abstract

Unconfined compressive strength (UCS) of rock is the most critical geomechanical property widely used as input parameters for designing fractures, analyzing wellbore stability, drilling programming and carrying out various petroleum engineering projects. The determination of UCS in the laboratory is a time-consuming and costly process. The current study aims to develop empirical equations to predict UCS using regression analysis by JMP software for the Khasib Formation in the Buzurgan oilfields, in southeastern Iraq using well-log data. The proposed equation accuracy was tested using the coefficient of determination ($R^2$), the average absolute relative error (AARE%) and the standard deviation error (SD%). It has been found that the developed equation is reliable and capable of predicting the UCS with an acceptable degree of confidence. $R^2$, AARE% and SD% are 0.8549, 2.619%, and 0.0569%, respectively when compared with field data. Furthermore, when compared to other known correlations, showed better prediction results.

Keywords: Unconfined compressive strength; Buzurgan oilfield; Log data; Water saturation; Electrical resistivity; Multiple regression

1. Introduction

The mud weight window, bit selection, and wellbore stability are all determined by unconfined compressive strength (UCS). Furthermore, it is critical for reservoir subsidence and acidification studies. When using UCS, it is critical to select the proper bit weight, as well as to evaluate drilling operation efficiency, bit wear, and efficient bit lifetime. It is described as the quantity of axial stress that a predetermined cylinder of rock can sustain before failing, and it is influenced by various parameters, including lithology, compaction, porosity, cementation, and fluid content (Nabaei et al., 2010; Awadh and Al-Auweidy, 2019). While practising wellbore stability evaluation, most issues include assessing rock mechanical properties, particularly the UCS (Rabbani et al., 2012). Numerous empirical formulae have linked the UCS of sedimentary rocks (sandstone, shale, limestone and dolomite) to physical parameters (i.e., velocity, modulus and porosity). These formulas can be utilized to calculate rock strength based on characteristics measured by geophysical well-logs (Chang, 2004). These equations

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can be utilized to determine rock strength and the benefit of compressional wave velocity (Vp) by using well-logging parameters (Zhang, 2006). As proposed, rock strength is obtained using the most commonly used parameters for compressive sound transit time, neutron porosity, bulk density, and gamma-ray for clay volume (Rabbani et al., 2012). Hassan et al. (2018) investigated various models such as multiple linear regression and artificial neural networks to estimate UCS using petrophysical logs data from one of the Iranian oil fields, the Asmari carbonate reservoir and then compared these methods. Rocks’ geomechanical properties are affected by fluid exposure. A decrease in UCS occurs when the water saturation increases (Yagiz and Rostami, 2012; Awadh, 2018). In previous decades, several authors connected many empirical correlations to determine the UCS, such as given by Smorodinov et al (1970); Militzer and Stoll (1973); Change (2004); Kahraman and Yeken (2010); Karamia et al. (2012); Zhang et al. (2017); Abdul Aziz and Abdul Hussein (2021). All of these UCS estimation models use different petrophysical properties as input data as shown below:

Smorodinov et al. (for carbonate rocks) (1970)  
\[ U_{CS} = 0.88 e^{2.85\rho} \]  
(1)

Militzer and stoll (1973)  
\[ U_{CS} = 2.45 V_{P}^{1.92} \]  
(2)

Change(2004)  
\[ U_{CS} = 143.8 e^{-6.95\rho} \]  
(3)

Kahraman and Yeken (2010)  
\[ U_{CS} = 0.081R + 58.28 \]  
(4)

Karamia et al.(2012)  
\[ U_{CS} = 35.35V_{s} - 7.58 \]  
(5)

Zhang et al.(2017)  
\[ U_{CS} = 22.104 x e^{-7.7825W} + 48.571 \]  
(6)

Abdul Aziz and Abdul Hussein (limestone)(2021)  
\[ U_{CS} = 20.35 - 0.948\rho \]  
(7)

Abdul Aziz and Abdul Hussein (limestone)(2021)  
\[ U_{CS} = 16.34\rho - 29.13 \]  
(8)

However, some researchers utilize multiple regression and produce encouraging results. This research aims to develop a single and multiple regression model to predict accurate UCS for the Khasib Formation (carbonate formation) in the Buzurgan oil field using conventional well-logs. This study uses JMP software to present a regression analysis, a statistical method for predicting UCS and effective petrophysical properties in a limestone formation (carbonate reservoir). Multiple regression will be discussed for accurate prediction of UCS in the investigated reservoir, as will the development of empirical models in which the measurable well logs can estimate UCS.

2. Location and Geological Setting

The Buzurgan oil field is situated in the Missan, southern Iraq (Fig. 1), near the Iranian border, 40 km northeast of Amara and 175 km north of Basra (Mohammed, 2018). The oilfield has 40 km long and has a width of 7 km. The Buzurgan structure is an NW-SE anticline parallel to the Zagros Mountains series, covering a total area of 394 Km² (Fig. 2) (Al-Ismaily, 2017; Jubair and Hadi, 2021).
Fig. 1. The oil/gas fields in Iraq. The red color is the study area, the Buzurgan oilfield (Mohammed, 2018)

Fig. 2. The Structure map of Buzurgan oil field (Jubair and Hadi, 2021)
The Khasib Formation in the Buzurgan oil field is dominated by massive limestone, with calcareous claystone at the bottom. It is mainly composed of CaO, SiO₂ and Al₂O₃ indicating an abundance of calcite, kaolinite and quartz. Claystone with limestone forms underlays Mishrif (MA) Formation. The Khasib Formation follows the Mishrif Formation composed of a lot of detrital supply. The Tanuma and Khasib formations belong to the Late Turonian-Early Campanian megasequence. The Khasib Formation is the most proximal unit of the late Turonian- Early Campanian Sequence (Chatton and Hart, 1961). The lower part (20m) of the formation consists of dark grey and greenish-grey shale, and, fine-grained, argillaceous limestone. The upper part (30m) comprises grey, fine-grained argillaceous limestones (Al-Mimar et al., 2018) (Fig.3).

![Fig. 3 The stratigraphic column of the Buzurgan oil field (Aldarraj and Almayahi, 2019)](image-url)
In many wells, the formation consists entirely of chalky and oligosteginal limestone, which lithologically similar to the Sadi Formation but of different biofacies. Its thickness increases towards the south of Iraq, and generally, decreases in the Tigris subzone of the Mesopotamian.

3. Statistical Evaluation

To model the output function, a collection of reservoir observations, such as well logs or core measurements, can be linked to the regression analysis. It is possible to use either a simple regression analysis or a multiple regression analysis. Multiple regressions are a type of regression analysis that adds another independent variable to the predictive equation (Abdul Majeed and Alhaleem, 2020). The JMP program was used to obtain the associations between UCS and physical rock properties using a sample of log data of physical rock parameters.

3.1. Single Linear Regression Analysis

Many designing and engineering issues exhibit that certain information fluctuates in an ascending or descending pattern. Many investigations have shown, for instance, that as UCS increases, so does the number of rock samples. Subsequently, it is beneficial to explore whether the UCS is related to petrophysical properties or not while assessing carbonate rocks utilizing a single linear regression.

3.1.1. Relation between UCS and porosity

Fig.4 presented the relationship between unconfined compressive strength (UCS) and porosity. This demonstrates that the porosity increases as the UCS decreases. The scattering around the curve can be attributed to the heterogeneity of carbonate, where the pore size distributions and void fractions inside the rock texture are complicated. The UCS and porosity relation has an $R^2= 0.934$, as clarified by the equation bellow:

$$UCS = 5.68 - 0.21 \times \phi$$

(9)

Where : $\phi$ is porosity, fraction.

![Fig. 4. Unconfined Compressive Strength (UCS) Vs. porosity](image-url)
3.1.2. Relation between UCS and bulk density

The relationships between UCS and rock density have been extensively studied. As illustrated in Fig. 5, UCS increases linearly with bulk density. The outcomes showed scattering around the bulk density-UCS curve. It can be attributed to the heterogeneity of carbonate formation. A good relationship exists between UCS and bulk density, with $R^2 = 0.841$. The relation's equation is as follows:

$$\text{UCS} = 11.5 \times \rho_b - 14.7$$

(10)

Where : $\rho_b$ the bulk density of the formation, gm/cc.

Fig. 5. Unconfined Compressive Strength (UCS) Vs. Bulk density

3.1.3 Relation between UCS and electrical resistivity

A strong linear relation between UCS and resistivity values (Fig. 6) as are positively correlated, as expressed by the equation below:

$$\text{UCS} = 13.47 + 0.0602 \times R_t$$

(11)

Where UCS in (MPa), $R_t$ is the electrical resistivity (Ω·m).

3.1.4. Relation between UCS and water saturation

Fig. 7 displays the average UCS value variations at various water saturation levels as they are negatively correlated, as shown in the equation below:

$$\text{UCS} = 17.43 - 0.05613 \times S_w$$

(12)

Where $S_w$ is water saturation, fraction
Fig. 6. Unconfined Compressive Strength (UCS) vs electrical resistivity

Fig. 7. Unconfined Compressive Strength (UCS) vs water saturation

3.2. Multiple Regression Analysis

To find more significant relationships than those found by simple regression, multiple regression analysis was used. Density, porosity, water saturation, and resistivity were included in the model. By using JMP software, the model was developed for estimating UCS using multiple regression. The software will find the relation between UCS and the parameters (Ø, ρb, Sw, and Rt), then look for equation coefficients (a, b, c, d, e, and f). The suggested equation could be as follow:

\[
UCS = a + b \times Rt + c \times (Rt + d)^2 + e \times \varnothing + f(\varnothing + g)^2 + h\rho_b + j \times Sw
\]  

(13)
Where $\Phi$ is neutron porosity expressed as a fraction, $\rho_b$ is bulk density in gm/cc, UCS is Unconfined Compressive Strength (UCS) in Mpa, Rt is electrical resistivity in $\Omega$ m, and $S_w$ is water saturation, fraction. Using the JMP software, Eq. 13 can be written as:

$$UCS = 11.362 + 0.013 \times Rt + 0.00023(Rt - 12.1669)^2 - 0.111 \times \Phi + 0.0039(\Phi - 7.1224)^2 + 1.547 \times \rho_b - 0.0107 \times S_w$$

(14)

4. Error Analysis

Two criteria have been used to evaluate this new correlation's overall performance and accuracy with those of the four. These criteria are (AbdulMajeed, 2014):

The average absolute relative error, Eq.19:

$$AARE = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{X_{measured}(i) - X_{calculated}(i)}{X_{measured}(i)} \right| \times 100\%$$

(15)

a. The standard deviation error, Eq. 20:

$$SD = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} \left[ \frac{X_{measured}(i) - X_{calculated}(i)}{X_{measured}(i)} \right] - AARE}^2$$

(16)

5. Model Outcome

For further validation, The new UCS prediction model given in Eq. 14 was compared with actual field data and four other known correlations available, as noted in the introduction (Militzer and Stoll, 1973; Kahraman and Yazan, 2010; Karamiah et al., 2012; Zhang et al., 2017), (Fig. 10). The developed model (eq.14) performs better agreement between field data and the new equation than empirical models, which can only be used to obtain an order of magnitude of the UCS.

![Fig. 8](image.png)

Fig. 8 Results of comparison between new correlation (Eq. 14) and other correlations with the actual data for Buzurgan well 28.
6. Results and Discussion

The predicted UCS using equation 14 gives a good match with measured UCS from log information as demonstrated in Fig. 9 with $R^2$ of around 0.8549. The corresponding UCS is computed using eq.14 and log UCS using the actual field versus depth for well 28 from the Buzurgan oil field (Fig.10). Multiple regressions demonstrated a strong correlation in predicting UCS from well-log information.

![Figure 9](image-url)

**Fig. 9.** UCS predicted using Multivariate regression equation (eq. (14)) Vs measured UCS from the log data for Buzurgan well 28.

Multiple regression is simply a generalization of the regression analysis that incorporates additional unbiased variables in the predictive equation. Empirical and multiple regressions were applied to log information to predict UCS for the carbonate reservoir. The statistical approach outperforms empirical models in terms of estimation, and it can be used exclusively to obtain a significant degree for UCS. The results shown in Fig. 8 and the obtained standard deviation percentage error between the new model and various known correlations for all examined formations could be gathered to provide the total standard deviation error shown in Fig. 11. A new correlation provides the most accurate results when compared to the other presented correlations. It gives a 0.0569% standard deviation error compared to the various other correlations. It is at least a double standard deviation error obtained by the new correlation. A new correlation has a lower average absolute relative error than the other correlations (Fig. 12). The current new model works at different reservoir conditions.
Fig. 10 Measured and predicted UCS using multivariate regression equation (Eq. (14)) Vs Depth

Fig. 11. Total standard deviation error percentage for the new model and the other four correlations
7. Conclusions

Using well-log data, the multiple regression analysis approaches used in this research reinforced a correlation between UCS and petrophysical properties. The most notable distinction between this research and prior studies is that the new model is based on four parameters: porosity, density, water saturation, and electrical resistivity, whereas previous research relied on the interaction between the two factors to impact UCS prediction. These findings are summarized as follows:

- It provides a more accurate correlation to determine UCS in the Khasib Formation of the Buzurgan oil field using traditional well-log information.
- The investigation found that UCS may be determined using a connection between porosity, density, water saturation, and electrical resistivity. UCS has a powerful correlation (0.8549) with this parameter when dipole substitution is unavailable. The predictors include UCS, which was developed to enhance the accuracy of the UCS prediction in the studied field. The consistency between the model and data outcomes, this model can be used to accurately predict the carbonate concentration in the reservoir.
- Comparing the effects of four well-known correlations with the new regression model shows that the new model (eq.14) is the most dependable model for UCS prediction compared to field data from the Buzurgan oilfield.

References


