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Using a novel approach to determine the pore pressure of West Qurna 15 oil well in South of Iraq

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ABSTRACT

Pore pressure means the pressure of the fluid filling the pore space of formations. When pore pressure is higher than hydrostatic pressure, it is named abnormal pore pressure or overpressure. When abnormal pressure occurred leads to many severe problems such as well kick, blowout during the drilling, then, prediction of this pressure is crucially essential to reduce cost and to avoid drilling problems that happened during drilling when this pressure occurred. The purpose of this paper is the determination of pore pressure in all layers, including the three formations (Yamama, Suliay, and Gotnia) in a deep exploration oil well in West Qurna field specifically well no. WQ-15 in the south of Iraq. In this study, a new approach of mechanical specific energy (MSE) was used to predict the pore pressure of the deep well WQ-15, and compare the results obtained with the previous techniques Magara, Eaton, Equivalent Depth and Sigma log along with the actual pore pressure using a statistical equation of Absolute Average Percentage Error (AAPE). The newly suggested approach obtained is good, and accepted results of pore pressure are encouraging to be applied in other oil wells rather than depending on previous traditional methods, especially when well logs are unavailable.

Keywords: Pore pressure, Formation pressure, Specific energy, West Qurna 15.

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استخدام محاولة جديدة لتحديد الضغط المسامي للبئر النفطي غرب القرنة 15 في جنوب العراق

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1. INTRODUCTION

Currently, the main target of any drilling operation is reducing the cost as well as avoid drilling issues or at least reduce the danger of drilling problems that might occur such as, blowouts, kick, stuck pipes, loss circulation, lost hole, and casing setting issues. West Qurna oil field is one of the largest oil fields in Iraq, with a reserve of about 43 billion barrels of crude oil. This field is located in the south-eastern part of Iraq, about 45 km north-westwards from Basra and 30 km from the Zubair oil field (Abd Al-Razzaq, A. Dabbaj, A. and Hadi, F., 2016).

Abnormal pressure is considered one of the issues that cause severe drilling dilemmas; therefore, predicting the pore pressure during drilling any well is significant to use the suitable drilling mud to control the well.

There are three types of pore pressure, including the following: 1-Normal pore pressure where the pore pressure gradient is very close to the hydrostatic formation pressure gradient, 2- Abnormal pore pressure where the pore pressure gradient is lower than the normal pore pressure gradient. If it is abnormally high, the pressure is called overpressure, or abnormally low or subnormal, where it is called surpressure.

Pore pressure gradient is depending on many factors such as: (temperature, concentration of dissolved salt in formation water, pore fluid sort), as illustrated by (Swarbrick and Osborne, 1998, and Louden 1972). (Teale, R., 1965) presented the idea of using Mechanical Specific Energy (MSE), or it is referred to as the Specific Energy (SE), which is defined as the quantity of energy needed to destroy a unit volume of rock. However, the SE doesn’t essentially represent the full energy used up in breaking the rock formation, because there are losses in hydraulic energy consumed by the drill bit while excavating the rock formation. The calculation of MES is affected by many factors such as toque (T), WOB (Weight on a bit), rotational speed, and ROP (Rate of penetration). The idea of MES used for many reasons such as 1- Assessing the performance of drilling operations 2-Evaluating the bit performance 3- studying the drilling infectiveness operations. (Amadi WK, Iyalla I -2012) MSE is used to explain the input quantity of energy employed in the drilling system. Specific Energy (SE) is studied where
laboratory tests have been performed to simulate the destruction of rock and the energy required to achieve that (Mohan, K., Adil, F., and Samuel, R., 2015).

(Cardona, J., 2011) was one of the researchers who used the Mechanical Specific Energy (MSE) idea to estimate the formation pore pressure rather than traditional approaches that depend on the d-exponent parameter. Cardona's model was appropriate for the case of merely strong rock environments.

While the specific energy way provides an easy way for suitable bits. It is well-defined as the demanded energy to remove one unit volume from the drilled rock. It can be taken any homogenous units according to (Assi, A., 2017), but Specific energy (SE), required energy was introduced for drilling rock volume, so this concept hasn't been considerably on rock studies as an index (Azike-Akubue, V., Barton, S., Gee, R., and Burnet, T., 2012).

(Majidi, R., and Last, N., 2017) suggested a methodology to determine the formation pore pressure from the combination of downhole drilling parameters as well as from in-situ rock properties using the concept of Drilling Efficiency (DE) and Mechanical Specific Energy (MSE). The formation pressure is believed to be a function of equivalent circulating density, MSE, uniaxial compressive strength, and angle of internal friction equation (1). The significant disadvantages of Majid's model are that there are several variables to be considered counting the petrophysical rock properties. The compressional wave velocity alone can provide an independent means of estimating the formation pore pressure. Majid's model takes no notice of the effect of hydraulic energy on the Rate of Penetration (ROP).

\[ P_p = \text{ECD} - \left( \text{DE trend} \times \text{MSE} \right) \left[ \frac{1 - \sin \theta}{1 + \sin \theta} \right] \]  

\[ \text{USC} = 0.43 \text{VP}^{3.2} \]  

\[ \Theta = 1.532 \text{ VP}^{0.5148} \]

where \( P_p \) is pore pressure, \( \text{ECD} \) is equivalent circulating density (ppg or psi/ft), \( \text{DE} \) is drilling efficiency, \( \text{USE} \) is uniaxial compressive strength, \( \Theta \) is the angle of internal friction, \( \text{VP} \) is the compressional velocity (m/s)

(Oloruntobi, O., Adedig, S., Khan, F., Chunduru, R., and Buttm S., 2018) introduced a new method to predict the pore pressure from drilling parameters. This method relied on the concept of Hydro-Mechanical Specific Energy (HMSE). The HMSE is the combination of axial, rotary, and hydraulic energies used to break and remove a unit volume of rock. Pore pressure prediction using the concept of HMSE is established on the theory that total energy consumed in breaking and removing a unit volume of rock beneath the bit. The new method can forecast the formation of pore pressure from the drilling parameters when reliable downhole measurements are missing.

2. THEORETICAL BACKGROUND

Historically, various approaches are used for pore pressure determination in oil wells. Three main formulas presented by (Ben, A., Eaton, 1972, and Ben, A., Eaton, 19725) are currently applied to quantify the formation pore pressure. The suggested three sets of equations for the determination of pore pressure are shown as follows:

\[ \text{Pp} = \text{ECD} - \left( \text{DE trend} \times \text{MSE} \right) \left[ 1 - \frac{\sin \theta}{1 + \sin \theta} \right] \]  

\[ \text{USC} = 0.43 \text{VP}^{3.2} \]  

\[ \Theta = 1.532 \text{ VP}^{0.5148} \]
where, Gpp is the predicted pore pressure gradient (psi/ft), Gob is the overburden pressure gradient (psi/ft), Gnp is the normal pressure gradient (psi/ft). Ro is the observed resistivity (ohm.m), Rn is the resistivity from the normal trend line, Δtn is the sonic transit time at the normal trend line (µsec./ft), Δt is the observed sonic transit time (µsec./ft), dco is the observed dc exponent values, and dcn is the dc exponent values from the normal trend line.

Abnormal pressure prediction could be achieved the specific energy technique which is based on the concept that overpressure intervals that have low effective stress need less energy to excavate than the intervals that have hydrostatic pressure at the same depth.

Eaton's formula for the forecasting of pore pressure is modified depending on the concept of specific energy as follows:

\[
Gpp = Gob - \{ Gob - Gnp \} \left[ \frac{R_o}{R_n} \right]^{1.2} 
\]

\[
Gpp = Gob - \{ Gob - Gnp \} \left[ \frac{\Delta t_n}{\Delta t} \right]^3 
\]

\[
Gpp = Gob - \{ Gob - Gnp \} \left[ \frac{dco}{dcn} \right]^{1.2} 
\]

(4)

(5)

(6)

The calculated values of formation pore pressure from Eq. (7) should be compared with other methods as well as with the actual pore pressure obtained from the Repeated Flow Test (RFT) and
from the Measurements While Drilling (MWD) logs. (Abbas, K., R., 1996) applied some techniques to predict the pore pressure gradient, such as (Magara, Eaton, Equivalent Depth, and Sigma log). To validate the robustness of the new suggested formula of pore pressure prediction a statistical analysis must be functioned to be used, where the determined pore pressure from the novel formula is compared to the actual formation pore pressure Absolute Average Percentage Error (AAPE) equation used for this purpose as follows:

\[
\text{AAPPE} = \left(1 - \frac{1}{N} \sum_{i=1}^{N} \left| \frac{A(I)_{m} - A(I)_{c}}{A(I)_{m}} \right| \right) \times 100
\]

(12)

where, AAPE is a percentage (%), \( A(I)_{m} \) is the measured (actual) value, \( A(I)_{c} \) is the calculated values, and \( N \) is the number of readings. This analysis can compare the calculated values for any model with the actual values where the model that has the lowest value of AAPE is the closest to the actual (Peter, J., Huber, 1964).

3. COLLECTION of DATA

The essential data used for the calculations in the present study were collected from the final bit record report as well as from the geological studies of West Qurna-15 deep well in the south of Iraq. The actual pore pressure is taken from the RFT and MWD logs. Data of Table (1) and (2) are quoted from the previous work of (Abbas, K., R., 1996 and Abbas, K., R., Hassanpour, A., Hare, C., 2014) while the data shown in Table(3) is also taken from the work of (Abbas, K., R., 1996).

Table 1. Data obtained from bit record, logs and geological information for WQ-15.

| Depth (m) | Overburden pressure, Gob psi/ft | Actual pore pressure, Gpp (psi/ft) | Bit commercial name | Bit type | The hardness of the bit, Ha (Gpa) | The hardness of bit (N/m²) | Formation |
|-----------|---------------------------------|-----------------------------------|---------------------|----------|---------------------------------|-----------------------------|------------|
| 2935      | 0.75                            | 0.4892                            | JD4                 | Milled-tooth | 12.95                             | 12950000000               | Nahr Umr  |
| 3110      | 0.75                            | 0.49188                           | JD4                 | Milled-tooth | 12.95                             | 12950000000               | Zubair     |
| 3205      | 0.75                            | 0.49235                           | S33                 | Milled-tooth | 12.95                             | 12950000000               | Zubair     |
| 3890      | 0.75                            | 0.67548                           | FS5 KJ              | Milled-tooth | 12.95                             | 12950000000               | Sulaik     |
| 4025      | 0.75                            | 0.76544                           | J33                 | Insert       | 15                                | 15000000000               | Sulaik     |
| 4085      | 0.75                            | 0.76623                           | J33                 | Insert       | 15                                | 15000000000               | Sulaik     |
| 4125      | 0.75                            | 0.793256                          | J3                  | Milled-tooth | 12.95                             | 12950000000               | Gotnia     |
| 4140      | 0.75                            | 0.81404                           | J33                 | Insert       | 15                                | 15000000000               | Gotnia     |
| 4255      | 0.75                            | 1.011488                          | J3                  | Milled-tooth | 12.95                             | 12950000000               | Gotnia     |
| 4286      | 0.75                            | 0.9824                            | J3                  | Milled-tooth | 12.95                             | 12950000000               | Gotnia     |
| Depth (m) | Pore pressure from Eaton (GPC1), psi | Pore pressure from Magara GPC2), psi | Pore pressure from Equivalent Depth (GPC3), psi | Pore pressure from SigmaLog (GPC4), psi |
|----------|------------------------------------|-------------------------------------|-----------------------------------------------|----------------------------------------|
| 2935     | 0.47754                            | 0.49885                             | 0.49573                                       | 0.770198                               |
| 2992     | 0.4464                             | 0.47578                             | 0.47881                                       | 0.440147                               |
| 3110     | 0.562178                           | 0.466                               | 0.47704                                       | 0.4804776                              |
| 3201     | 0.54348                            | 0.5447                              | 0.53629                                       | 0.4842357                              |
| 3205     | 0.53427                            | 0.53617                             | 0.53095                                       | 0.4822636                              |
| 3575     | 0.6817                             | 0.5739                              | 0.57169                                       | 0.59941                                |
| 3710     | 0.69545                            | 0.583776                           | 0.578887                                      | 0.5988495                              |
| 3874     | 0.57393                            | 0.5815                              | 0.579758                                      | 0.714267                               |
| 3890     | 0.75908                            | 0.5854                              | 0.7588                                        | 0.7959568                              |
| 3915     | 0.765276                           | 0.7726                              | 0.7943                                        | 0.8117358                              |
| 3940     | 0.79865                            | 0.7699                              | 0.794209                                      | 0.8300221                              |
| 4025     | 0.7621                             | 0.76135                             | 0.7842218                                     | 0.8149517                              |
| 4050     | 0.760484                           | 0.76928                             | 0.7882                                        | 0.8147386                              |
| 4085     | 0.73834                            | 0.7845                              | 0.80392                                       | 0.7954028                              |
| 4115     | 0.81566                            | 0.7834                              | 0.80538                                       | 0.8417547                              |
| 4125     | 0.8051004                          | 0.80308                            | 0.82742                                       | 0.838145                               |
| 4140     | 0.84723                            | 0.79813                             | 0.821018                                      | 0.8854011                              |
| 4211     | 1.010074                           | 0.99307                             | 0.99166                                       | 0.9783616                              |
| 4255     | 1.00831                            | 1.00843                             | 0.99899                                       | 0.9750899                              |

Table 2. Main rock formations being penetrated in WQ-15 with the corresponding rock hardness.

| Rock formation  | Hardness (Gpa) |
|-----------------|----------------|
| Sandstone       | 10.79          |
| Limestone       | 1.079          |
| Dolomite        | 2.45           |
| Shale           | 1.961          |
| Anhydrite       | 1.569          |
| Conglomerate    | 1.17           |

Table 3. Pore pressure obtained from various methods of Eaton, Magara, Equivalent depth and sigma log for WQ-5.
4. METHODOLOGY

1- The first step is to calculate the values of the observed specific energy (SEo) from Eq. (11). The results are shown in Table (4).

2- A normal compaction trend line is drawn to extract the values of the normal specific energy (SEn) that decreases gradually with depth. The results are displayed in Table (4) and Fig. (1).

3- Computation of the exponent (m) is achieved by drawing Log \([(Gob-Gpp)/(Gob-Gnp)]\) vs. Log [SEo/SEn] and then plotting the best line through the points by Excel, where the slope of the best line is (m). The slope was found to be 1.043. Fig. (2) shows the plot and the best line through the points.

4- Eq. (7) was used to calculate the pore formation pressure (Gpp) based on specific energy. The produced results are demonstrated in Table (5).

5- Plotting the pore pressure (Gpp) obtained from Eq. (7) along the actual pore pressure taken from well logs versus depth. This plot is shown in Fig. (3).

6- The Absolute Percentage Error (AAPE) was calculated from Eq. (12) for the new model based on (SE) and also for all the previous techniques being used to predict the pore pressure for WQ-15 i.e. Magara, Eaton, Equivalent Depth and Sigma log, where this statistical equation compares between the measured and the calculated values to reveal the robustness of the model that is closest to the measured or actual values.

7- Plotting the pore pressure obtained from Magara, Eaton, Equivalent Depth, and Sigma log methods as well as the newly developed approach with actual pore pressure taken from RFT and MWD logs versus depth. This plot is illustrated in Fig. (4).
5. RESULTS and DISCUSSION

The plot of SE (Specific Energy) obtained from the new model versus depth is displayed in Fig. (1). The SE values are computed from Eq. (11). In this well, the specific energy is affected by the hardness of the rock formation as well as the hardness of the bit that excavates the well. The normal compaction trend line (NTC) is drawn for the values of SE been decreasing gradually from 2895 m to 3895 m, whereas SE decreases with depth, while below 3895 m, i.e., top of overpressure zone, the specific energy starts to undergo departure from NTC to lower values. This is attributed to the occurrence of subsurface overpressure conditions. In this formation, the amount of rock compaction is reduced, leading to an increase in pore pressure and decreases specific energy that is required to remove the unit volume of rock. Fig. (2) shows the determination of the exponent (m) in Eq. (11). Fig. (2) illustrates that the value of (m) produced was log11.063, which means m = 1.043. Fig. (3) displays the plot of the pore pressure resulted from the new suggested formula with the actual pore pressure versus depth. The actual pore pressure measurements were taken from MWD and RFT logs. It is worth mentioning that pore pressure values produced from the new approach are close to the actual in-situ pore pressure.

Fig. (4) displays a comparison between pore pressure obtained from previous approaches with the novel method along with actual formation pressure versus depth. Previous methods are Eaton GPC1, Magara GPC2, Equivalent Depth (GPC3), and Sigma log (GPC4). The Results of the pore pressure obtained from previous methods are demonstrated in Table (3), while the results of the new method (dependent on specific energy) are displayed in Table (5). A statistical analysis using the implication of AAPE (Absolute Average Percentage Error) is applied to clarify the degree of convergence of each method with the actual pore pressure. APPE is calculated from Eq. (12). This equation is used to compare measured values with the calculated ones for any model. Therefore, the model that has the lowest APPE is considered the best among the models. Results of APPE for the previous techniques were (3.811%, 3.9104 %, 2.1348 %, 3.0935 %, and 5.628 %), referring to the new model based on SE, Eaton, Magara, Equivalent Depth, and Sigma log respectively. Although, from the APPE values, it is shown that the new approach for pore pressure determination is considered a good and reliable approach as it has very low AAPE, i.e., 3.811 % compared with other methods. On the other hand, the pore pressure gradient calculated by Sigma log is the worst, according to APPE. The abnormal pore pressure in well WQ15 is found to be in Yamama, Suliay, and Gotania formations as concluded by (Abbas, K., R., 1996).

Pore pressure gradient calculated by the method presented in this research is considered a good approach to predict pore pressure in case of the unavailability of well logs.
Table 4. Results of observed and normal specific energy.

| Depth (m) | Observed specific energy (SEo), Mpsi | Normal specific energy (SEn), Mpsi |
|-----------|-------------------------------------|-----------------------------------|
| 2935      | 175328.1578                         | 170340                            |
| 2992      | 159083.7719                         | 156310                            |
| 3110      | 159083.7719                         | 151270                            |
| 3201      | 159083.7719                         | 151280                            |
| 3205      | 138186.9306                         | 102960                            |
| 3890      | 78382.5948                          | 101690                            |
| 3915      | 65086.52311                         | 102950                            |
| 4025      | 65501.65226                         | 92800                             |
| 4050      | 46525.74901                         | 88980                             |
| 4085      | 42271.34747                         | 86440                             |
| 4115      | 42545.96323                         | 83896                             |
| 4125      | 61235.97021                         | 82625                             |
| 4140      | 61037.93305                         | 82610                             |
| 4211      | 43657.18112                         | 80085                             |
| 4255      | 8265.537429                         | 73728.8                            |
| 4268      | 3572.407604                         | 72440                             |
| 4286      | 3078.003329                         | 72470                             |
| 4291      | 14766.59663                         | 72460                             |
| 4304      | 4727.465597                         | 72450                             |
| 4325      | 7800.924068                         | 69920                             |
| 4360      | 8749.587679                         | 67370                             |
| 4368      | 13447.13414                         | 66110                             |
| 4375      | 10226.49205                         | 66100                             |
| 4390      | 13532.99923                         | 64830                             |
| 4395      | 3499.681255                         | 63559                             |
| 4400      | 24116.83674                         | 66101.69                           |
| 4413      | 30085.29073                         | 63560                             |
| 4431      | 26983.33134                         | 61020                             |
| 4439      | 26002.22041                         | 61010                             |
| 4526      | 27990.60357                         | 55932                             |
| 4550      | 26002.22041                         | 53380                             |
**Figure 1.** Specific energy obtained from the new formula versus depth.

**Figure 2.** Log \(((\text{Gob-Gpp})/(\text{Gob-Gnp}))\) versus Log \([\text{SEo}/\text{SEn}]\).
Table 5. Results of pore pressure depended on specific energy.

| Depth (m) | Pore pressure gradient predicated |
|-----------|----------------------------------|
| 2935      | 0.492667218                      |
| 2992      | 0.508698625                      |
| 3110      | 0.476428006                      |
| 3201      | 0.486987105                      |
| 3205      | 0.516955973                      |
| 3874      | 0.619316321                      |
| 3890      | 0.713799056                      |
| 3915      | 0.695072302                      |
| 4025      | 0.776396101                      |
| 4050      | 0.792334882                      |
| 4085      | 0.783235032                      |
| 4115      | 0.63576808                       |
| 4125      | 0.824082437                      |
| 4140      | 0.826788259                      |
| 4211      | 1.00004279                       |
| 4255      | 1.028344694                      |
| 4268      | 1.028389191                      |
| 4286      | 0.947560144                      |
| 4291      | 1.01963841                       |
| 4304      | 0.998712085                      |
| 4325      | 0.989823289                      |
| 4360      | 0.950628357                      |
| 4368      | 0.973622882                      |
| 4375      | 0.947861971                      |
| 4390      | 1.025947209                      |
| 4395      | 0.85153643                       |
| 4400      | 0.80743737                       |
| 4413      | 0.825365111                      |
| 4431      | 0.82443513                       |
| 4439      | 0.850417695                      |
| 4526      | 0.841076778                      |
| 4550      | 0.849291995                      |
Figure 3. Pore pressure predicated by SE method with actual pore pressure vs. depth.

Figure 4. Comparison of various methods of pore pressure determination along with the actual pore pressure versus depth.
CONCLUSIONS

1-Specific energy technique is concluded to be a good and acceptable approach to estimate pore pressure gradient, especially when well logs are unavailable.
2- From the results, the new approach was found to be close to the actual pore pressure as the percentage error is logically acceptable.
3- It is possible to calculate the SE values from other equations found by Teale and Rabia. The previous equations depended on the drilling parameters, whereas the equation used in the present research depends only on the hardness of the rock formation and the hardness of the drill bit.

NOMENCLATURE

ECD  equivalent circulating density (ppg or psi/ft)
DE  Drilling Efficiency
USE  uniaxial compressive strength
θ  angle of internal friction
Vp  compressional velocity (m/s)
NTC  normal compaction Trend line
Dc  \( \cot(x)/r \) – exponent
Dcn  dc – exponent from the normal compaction trend at a given depth
Dco  computed dc – exponent from the measured data at a given depth
M  HMSE exponent
MWD  measurement while drilling
RFT  repeated Flow test
MES  mechanical specific energy (psi)
HMSE  hydro-mechanical specific energy (psi)
APPE  absolute Average percentage error
Gnp  normal pore pressure gradient at a given depth (psi/ft)
Gob  overburden pressure gradient at a given depth (psi/ft)
Gpp  pore pressure gradient at a given depth (psi/ft)
Hw  hardness of bit
Ha  hardness of rock formation
SEo  specific energy observed
SEn  normal Specific energy
GPC1  pore pressure gradient (Eaton method ) psi/ft
GPC2  pore pressure gradient (Maraga method ) psi/ft
GPC3  pore pressure gradient (Equivalent Depth Method ) psi/ft
A(I)m  measured values (actual value)
A(I)c  calculated value
APPE  absolute Average Percent Error
N  number of values
Ro  observed shale resistivity at a given depth (ohm – m)
Rn  normal compaction trend shale resistivity at a given depth (ohm – m)
ROP  rate of penetration (ft/hr)
T  torsion or torque (lb-ft)
Δtn  normal compaction shale travel time at a given depth (microsecond – ft)
Δto  observed shale travel time at a given depth (micro-second/ft)
Pp  pore pressure

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