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Predictive study to identify the sanding initiation threshold depending on physical and mechanical rock characteristics

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ABSTRACT

Sand production is an undesirable phenomenon that occurs in wellbores extracting resources from sandstone formations. It presents a significant challenge to the advancement of oil and gas operations. The main implications of sand production include the disintegration of geological formations, deterioration of both surface and downhole systems, reduced hydrocarbon extraction efficiency, and various environmental concerns. These challenges can result in annual costs amounting to billions of dollars for the petroleum industry. Motivated by these issues, this study conducted a field case study in southern Iraq to introduce predictive techniques based on geomechanical and physical properties to anticipate and mitigate the risk of sand production hazards. Moreover, seven threshold criteria were utilized to identify the critical limits at the onset of sanding. These criteria include unconfined compressive strength (UCS), total porosity (PHIT), shear modulus and rock compressibility ratio, sonic compression wave, B-index, S-index, and Ec-index. Additionally, some of these techniques are strongly related to elastic and strength rock parameters; hence, to perform them accurately, more appropriate correlations were used for the area of interest. The results indicate that sand production is likely to occur when the threshold values for the UCS, B-index, and S-index fall below 4,200 psi, 1.6 × 106 psi, and 9.2 × 109 psi, respectively, while the PHIT value exceeds 20%. Finally, this investigation can serve as a guide for optimizing sand management to achieve maximum completion performance.

KEYWORDS

Sand production, mechanical and physical rock properties, geomechanical parameters, well logging, sanding risk

I. INTRODUCTION

More than 60% of oil and gas wells in the Middle East are derived from sandstone formations; this percentage increases to 70% when considering all global fields (Nouri et al., 2003; Osisanya, 2010). Historically, sand production has been an issue linked to inadequately cemented formations. This phenomenon significantly impacts hydrocarbon production, potentially leading to severe complications in oil or gas flow within a reservoir and impairing the effective operation of production equipment (Adil Issa et al., 2022). Moreover, the primary cause of sand production is the instability of the wellbore, along with failure of the perforation tunnel in both unconsolidated and weakly consolidated reservoirs (Subbiah et al., 2021). Therefore, assessing in-situ stresses, including vertical stress and minimum and maximum horizontal stresses, along with the mechanical properties of rock, specifically strength properties like cohesiveness, friction angle, and unconfined compressive strength, presents challenges due to fluctuations in these parameters during field operations (Aadnoy & Looyeh, 2019; Issa, Issa, et al., 2023). These fluctuations arise from reservoir pressure depletion caused by hydrocarbon extraction. Additionally, the elastic characteristics of the rock, which include bulk and shear moduli, Poisson's ratio, and Young's modulus, further complicate these assessments (Zhang, 2019; Zoback, 2007). Consequently, understanding the geomechanical parameters, i.e., in-situ stresses, pore pressure, and mechanical rock properties of subsurface strata, is essential for several geomechanical applications, including wellbore stability analysis, hydraulic fracturing, sand production prediction, reservoir compaction, and subsidence (Issa, Hadi, et al., 2023).

Sand production results from the breakdown of sand grains within the rock formation surrounding the wellbore, regardless of the completion type used (Tronvoll et al., 2001). Sand production can be classified into three distinct categories: transient sand production, continuous sand production, and catastrophic sand production. These categories describe different phenomena: transient sand production is characterized by a decline in sand production over time; continuous

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sand production indicates sustained levels of sand production; and catastrophic sand production involves escalating rates of sand influx that can lead to the abrupt choking or cessation of the well (Al-Awad, 2001). Additionally, sand production may occur due to various well activities or changes in the reservoir caused by production depletion. Therefore, understanding these aspects is essential for comprehending this phenomenon and developing effective sand control treatments and management techniques (Issa et al., 2024).

Multiple parameters can be utilized to ascertain the optimal strategy for mitigating sand production, including sand classification (fine or coarse), permeability alterations within the reservoir, pay-zone thickness, borehole deviation, and accessibility to a workover rig (Osisanya, 2010). Traditional sand control methods mostly involve the installation of sand screens, frac-packs, and gravel packs (Issa et al., 2022). Two approaches are employed for sand control: a mechanical technique, as mentioned above, and a chemical method (sand stabilization through chemical consolidation). However, it is necessary to forecast the stability of the perforation and the likelihood of sanding prior to the completion engineers' determination of the required sand management techniques (Salahi et al., 2021). Sand management involves balancing the risks (i.e., safety, environmental impact, cost, and operational processes) related to sand production from the reservoir to the surface. Furthermore, it aims to mitigate the risks related to retaining sand within the reservoir (Mahmud et al., 2020). Consequently, predicting sand production is beneficial for the development of oil and gas fields that extract resources from sandstone formations with low to intermediate strength.

In recent decades, significant research has focused on creating models (e.g., Adeyanju & Oyekunle, 2010; Najibi et al., 2017; Okereke et al., 2020; Palmer et al., 2003; Yi et al., 2004) to estimate sand production based on various factors, including formation stress and strength, reservoir pressure, production rate, formation properties, fluid types, pressure drawdown, and other pertinent variables. These models assist in various field operations, such as sand production control, optimization of well completion design, and enhancement of overall production. However, no existing model can assess the risk of sanding under specific field conditions. This study was prompted by the potential for local implementation of mentioned models. A field case study in southern Iraq was conducted to predict the possibility of sanding risk by identifying threshold of mechanical and physical rock properties. Furthermore, the primary difference between this study and others is in its comprehensive methodology for identifying intervals capable of generating sand over time, based on physical and geomechanical parameters. Consequently, these intervals must be managed prior to executing workover operations to prevent sand formation complications. The Zubair Formation, one of the most critical reservoirs within the X field, and its lithology comprises mostly sandstone and shale intervals; it was the focus of this study.

II. Materials and Methods

A. *Problem Statement and Methodology*

Sand production has become a significant challenge for the oil and gas industry. This issue is particularly evident in wells extracting hydrocarbon fluids from sand deposits. It can cost the petroleum industry billions of dollars annually due to the decline in hydrocarbon recovery, workover operations, and the activities associated with repairing and reinstalling Electrical Submersible Pumps (ESP), as well as the need for environmentally compliant sand disposal. Consequently, this predictive study was initiated to mitigate the risks of sand production over time in the X oilfield, located in southern Iraq. The study focuses on determining the sanding commencement cutoff based on the physical and mechanical properties of the reservoir rock.

The geological layers in the southern Iraq fields consist of a complex sequence of sedimentary strata that spans from the Jurassic to the Cretaceous and Tertiary periods. These sedimentary deposits comprise various sedimentary rocks, including sandstone, limestone, and shale. These deposits facilitate the development of geological formations that encompass oil and gas (Jassim & Goff, 2006). The Zubair formation belongs to the Cretaceous epoch, which is a significant clastic reservoir in southern Iraq that holds substantial hydrocarbon reserves. It has a gross vertical thickness of approximately 450 meters. Its lithology primarily consists of shale, interbedded with sandstone layers, as well as some siltstones and limestone. This study focuses on the sandstone interval within the reservoir, extending from 3310 to 3420 meters.

B. The study used seven threshold criteria to identify the initiation of sand production based on the mechanical and physical properties of rock. These criteria include compressional sonic wave (CSW), unconfined compressive strength (UCS), total porosity (PHIT), the ratio of shear modulus to bulk compressibility (G/C_b), B-Index, Schlumberger index (S-Index), and combined index (Ec-Index). To conduct the study, which involves applying the seven threshold techniques mentioned, datasets extracted from a single well (i.e., bulk density measurements and compressional and shear sonic waves) were utilized to calculate geomechanical characteristics and construct profiles for the threshold criteria. Moreover, some of these criteria required values for unconfined compressive strength (UCS) and static Young's modulus (E). To determine the most appropriate correlations for these geomechanical parameters, several empirical correlations from the literature were calibrated using core data collected from various depths within the study area.

C. Methods of Sand Production Prediction

To mitigate sand production, it is imperative to identify prospective sand-producing zones; therefore, comprehending the operating limits necessary to prevent sand production is vital. This study employs various techniques:

1) Unconfined Compressive Strength (UCS)

Continuous profiles of mechanical rock properties are essential throughout various phases of well and reservoir life, including drilling, production, and enhanced reservoir modeling. Mechanical properties of rocks are usually categorized based on their distortion regime into two categories: elastic properties and strength properties. Unconfined Compressive Strength (UCS) is one of the key strength property of rock and is utilized in various geomechanical applications, as it serves as a critical indicator of rock strength. According to Edimann et al. (1998), sanding is probable when the UCS is below 7,250 psi (50 MPa). Numerous empirical equations have been introduced in the literature to determine the unconfined compressive strength (UCS) for various lithology's. These correlations are based on the physical and mechanical properties of rock data (Table 1).

2) Total Porosity (PHIT)

Several studies have outlined a specific empirical method for identifying the onset of sanding issues. This method indicates that sandstone formations with a total porosity (PHIT) greater than 30% have a significant potential for sand production, while those with a porosity range of 20%–30% show a limited likelihood of sand production. Consequently, formations with a PHIT exceeding 30% are at considerable risk of substantial sand production if sand management techniques or equipment are not available in the area of interest (Hong'en et al., 2005). Total porosity can be determined from density-neutron logs using Eq. (12), where PHID is the density porosity; and PHIN is the neutron porosity.

$$PHIT = \sqrt{\frac{PHID^2+PHIN^2}{2}} \quad (12)$$

It can also be determined using sonic log (Eq. (13)), where Δt_{log} the measured transit time is obtained by sonic log, Δt_{ma} is the rock matrix transit time, and Δt_f is the pore fluid transit time (Wyllie et al., 1956).

$$PHIT_s = \frac{\Delta t_{log}-\Delta t_{ma}}{\Delta t_f-\Delta t_{ma}} \quad (13)$$

3) Shear Modulus and Rock Compressibility Ratio (G/C_b)

As per Tixier et al. (1975), G and C_b are essential elastic parameters for diagnosing sanding problems. These parameters are employed to forecast sand production by identifying the critical threshold of the rock, and their calculation is normally dependent on well log data. Case studies performed on North Sea fields indicate that sand formation is probable when the threshold ratio of $\frac{G}{C_b}$ drops below 0.8×10^{12} psi^2. Eq. 14 was employed to calculate G/C_b, which relies on the static Poisson's ratio (v) and static Young's modulus (E).

$$\frac{G}{C_b} = \frac{E^2}{6\,(1+v)(1-2v)} \quad (14)$$

In the present study, the static Poisson's ratio (Eq. 15) and the dynamic Young's modulus (Eq. 16) for the area of interest were calculated using well-logging data, specifically bulk density and sonic log readings (Fjar et al., 2008; Issa et al., 2025).

Table 1. Illustrate the UCS empirical correlations for sandstone formation.

Eq. no.	Equation (MPa)	Developed region	Reference
1	$UCS = 0.035V_p - 31.5$	Thuringia, Germany	Freyburg (1972)
2	$UCS = 1200\,exp(-0.036\Delta t)$	Bowen Basin, Australia	McNally (1987)
3	$UCS = 1.4138 \times 10^7\,\Delta t^{-3}$	Gulf Coast	Fjar et al. (2008)
4	$UCS = 1.745 \times 10^{-9}\,\rho\,V_p^2 - 21$	Cook Inlet, Alaska	Moos et al. (1999)
5	$UCS = 42.1\,exp\,(1.9 \times 10^{-11}\,\rho\,Vp^2)$	Australia	Moos et al. (1999)
6	$UCS = 3.87\,exp(1.14 \times 10^{-10}\,\rho\,Vp^2)$	Gulf of Mexico	Bradford et al. (1998)
7	$UCS = 46.2\,exp\,(0.027E)$	-	Bradford et al. (1998)
8	$UCS = 2.28 + 4.1089E$	Worldwide	Vernik et al. (1993)
9	$UCS = 254\,(1 - 2.7\varphi)^2$	Sedimentary basins worldwide	Vernik et al. (1993)
10	$UCS = 277\,exp\,(-10\varphi)$	-	Vernik et al. (1993)
11	$UCS = 3.3348\,E^{1.6081}$	Southern Iraq	Issa & Hadi (2021)

Where V_p is the compressional wave velocity, Δt is the sonic compressional wave, ρ is the bulk density, E is the static Young's modulus, and φ is the porosity.

$$v = \frac{(V_p^2 - 2V_s^2)}{2(V_p^2 - V_s^2)} \quad (15)$$

$$E_{dyn} = \frac{\rho_b\ V_s^2\left(3V_p^2 - 4V_s^2\right)}{(V_p^2 - V_s^2)} \quad (16)$$

Where ρ_b is the bulk density (gm/cc), and V_s & V_p are shear and compressional wave velocities, respectively (Km/s).

Regarding the static Young's modulus (E), several empirical equations have been proposed in the literature for diverse formation lithologies. These correlations are derived from physical and mechanical rock data (see Table 2).

Table 2. Illustrates the static Young's modulus correlations for sandstone formation.

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Eq. no.	Equation (Gpa)	Reference
17	$E = 0.74\ E_{dyn} - 0.82$	Eissa & Kazi (1988)
18	$E = 0.061\ E_{dyn} + 0.00285$	Gorjainov & Ljachowickij (1979)
19	$E = 0.41\ E_{dyn} - 1.06$	Wang & Nur (2000)
20	$E = 0.0293\ E_{dyn}^2 + 0.4533\ E_{dyn}$	Lacy (1997)
21	$E = 0.0018\ E_{dyn}^{2.7}$	Bradford et al. (1998)
22	$E = -0.02\ E_{dyn}^2 + 2.1356\ E_{dyn} - 25.296$	Issa & Hadi (2021)
23	$E = 0.64E_{dyn} - 0.32$	Eissa & Kazi (1988)
24	$E = 0.69E_{dyn} + 6.40$	McCann & Entwisle (1992)
25	$E = 1.05E_{dyn} - 3.16$	Christaras et al. (1994)
26	$E = 0.7707E_{dyn} - 5854$	Mockovčiaková & Pandula (2003)
27	$E = \exp\ (0.0477E_{dyn})$	Soroush & Fahimifar (2003)
28	$E = 0.867E_{dyn} - 2.085$	Brotons et al. (2014)
29	$E = 0.932E_{dyn} - 3.421$	Brotons et al. (2016)

4) Compressional Sonic Wave (CSW)

CSW (in µs/ft) may operate as a predictor for the initiation of sanding. If the CSW surpasses 89.9, sand production is anticipated; alternatively, production would remain devoid of sand (Dong et al., 2013). Nonetheless, a study by Al Said Naji et al. (2023) revealed different threshold values, suggesting that sand remains stable and does not generate if CSW is ≤95. Additionally, sand production has potential when CSW is between 95 and 105, whereas it is guaranteed when CSW surpasses 105. These discrepancies in threshold levels are ascribed to changes in formation characteristics.

5) B-index Technique

Acquiring core specimens from specific unconsolidated sand layers can be challenging. Consequently, well log data can be used to determine the B-index as an indicator of the potential for sanding. A higher B-index value signifies a stronger formation. Research shows that a B-index below 2.9 × 10^6 psi (≈20000 MPa) is associated with an increased likelihood of sanding concerns. Thus, the lower values of the B-index refer to a greater probability of sand production. The B-index can be calculated using Eq. 30, (Dong et al., 2013).

$$B - index = \frac{E}{(3-6\ v)} + \frac{4E}{(6+6\ v)} \quad (30)$$

6) S-index Technique

Upon extensive testing of oil wells located in the Gulf of Mexico, Schlumberger implemented the subsequent methodology: The sanding is anticipated when the S-index is below 4.79 × 10^9 psi. The S-index is calculated using Eq. 31, where ρ_b is the bulk rock density (gm/cc); v is the Poisson's ratio; and DTc is the compressional sonic wave (us/ft), (Hong'en et al., 2005).

$$S - index = \frac{\left(9.94\times10^8\right)^2(1-2v)(1+v)\rho_b}{6(1-v)^2\ DTc^4} \quad (31)$$

7) Ec-index Technique

The combined modulus (Ec-index) is an empirical approach for forecasting sand production, employing well-logging observations to determine the Ec-index. A threshold limit of the Ec-index signifies the absence of sand generation whenever it is higher or identical to 0.288 × 10^6 psi. If the value falls between 0.216 × 10^6 psi and 0.288 × 10^6 psi, moderate sand production is anticipated; conversely, high sand production is likely when the value is below 0.216 × 10^6 psi. The following formula (Eq. 32) was used to calculate the combined modulus (Hong'en et al., 2005).

$$E_c - index = \frac{9.94\times10^8\ \rho_b}{DTc^2} \quad (32)$$

III. Results and Discussions

The purpose of developing an extensive number of empirical and theoretical methods is to facilitate the prediction of sand production. For these procedures to work, data gathered from well logs, the results of core sample examinations, and observations conducted in the area of interest are necessary. Furthermore, it is difficult to accurately forecast sand production throughout the entire well exploitation phase using a singular method. Therefore, integrating several techniques can attain optimal accuracy for prediction. However, to determine the sanding threshold and intervals posing the possibility of sand production, the present investigation employed seven empirical methodologies.

The UCS is the first technique used to identify the sand production threshold, but the challenge with this technique is how to select the optimum UCS correlation that is appropriate for the area of study. To overcome this issue, a set of UCS correlations specific to sandstone formations was collected, as mentioned previously shown in Table 1. A more precise correlation for the area of interest was identified by validating these correlations against core data obtained from different depths within the area of study, as illustrated in Fig. 1. Based on the matching results, Eq. 3 gives reasonable agreement with the core samples data, and it was therefore selected to calculate the UCS profile.

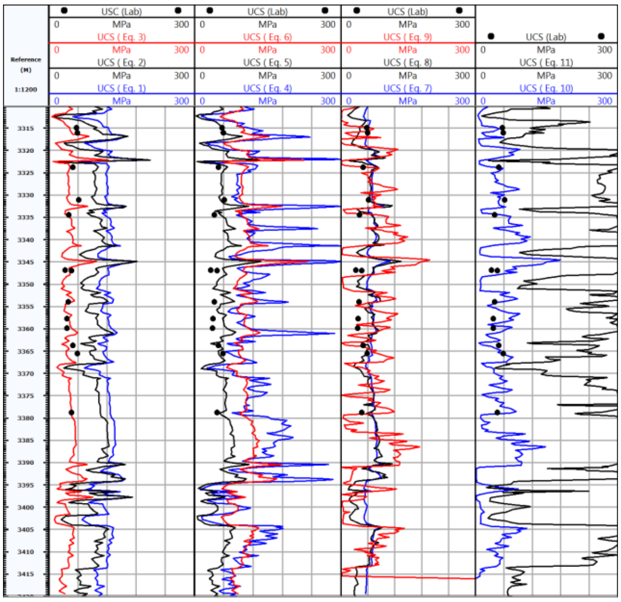

Fig. 1. Illustrates UCS correlations against the core data

Fig. 2 illustrates the threshold limits identified by two methods, namely UCS and PHIT, for predicting the onset of sanding. Based on the UCS profile constructed using Eq. 3, the critical limit is set at 4200 psi (as shown in the first track of Fig. 2). This means that values exceeding this critical threshold indicate that the formation rocks exhibit greater resistance to failure. In contrast, any value below the critical limit suggest that sand production may occur.

Regarding the second method (PHIT), two methods were previously proposed to calculate total porosity. The initial method for calculating porosity utilized a combination of density and neutron logs. The hydrogen content aids in estimating porosity, therefore making the neutron log beneficial. In low-porosity strata, the neutron log significantly exaggerated porosity, leading to considerable difficulty in establishing a reliable cut-off value. Regarding the second approach, the velocity of acoustic waves, measured by the sonic log, significantly influences porosity, with clay content having a minimal impact. In contrast to results from alternative methodologies, the sonic log showed better alignment with production data; therefore, it was the most beneficial method. The main limitation of the neutron log makes the sonic log a more favorable choice for porosity assessment. Consequently, the total porosity was calculated in this study based on sonic log measurements using Eq. 13. The second track of Fig. 2 shows that PHIT identified a threshold limit of 20%. If any value surpasses this critical total porosity threshold, sand production will take place. Furthermore, it can be inferred that formation rocks with lower unconfined compressive strength (UCS) and higher porosity are more susceptible to fracturing and sand production.

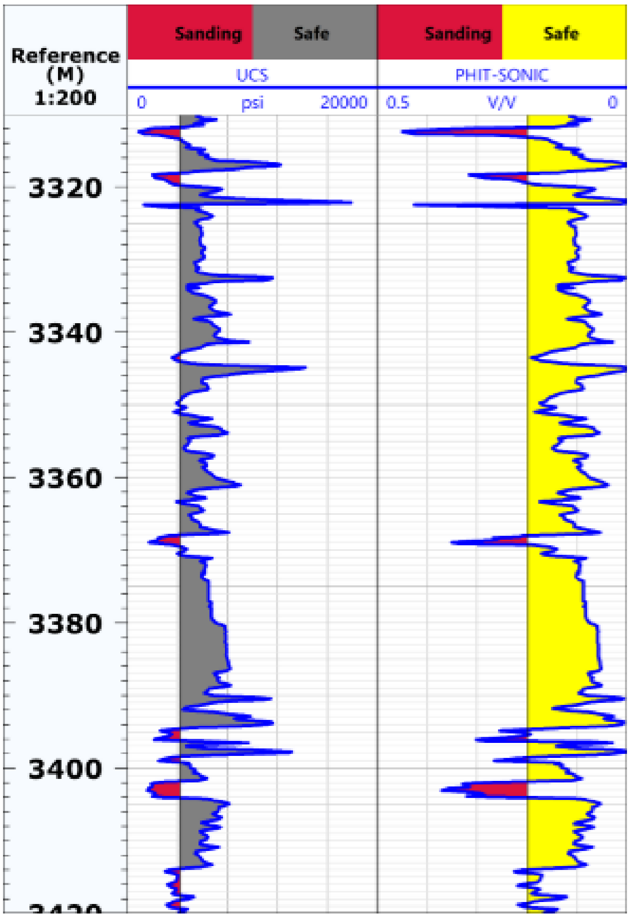

Fig. 2. Demonstrates the critical limit of sanding using UCS and PHIT techniques

The third technique used in this investigation is the ratio of shear modulus to rock compressibility (G/C_b), calculated using Eq. 14. This technique relies on the computation of some of the geomechanical parameters, i.e., static Poisson's ratio and static Young's modulus.

The profile of static Poisson's ratio was constructed using Eq. 15. Regarding the static Young's modulus, this investigation collects a set of static Young's modulus correlations that are designed as a function of dynamic Young's modulus (Table 2). These correlations are specifically designed for sandstone formations. Thus, a more accurate correlation for the area of interest was selected through calibration of all these correlations against core data points extracted from different depths within the area of interest, as shown in Fig. 3. Based on the matching results, Eq. (23) shows reasonable agreement with the core sample data. Consequently, in this study, the dynamic Young's modulus was computed based on well logging data using Eq. (16), and Eq. (23)

was used to calculate the static Young's modulus according to the calibrated results (Fig. 3).

Additionally, both equations (Eqs. 3 and 23) were formulated or modified using models that integrate essential petrophysical factors (e.g., sonic transit time, bulk density), which are recognized to possess a direct and physically significant correlation with rock strength and stiffness. These correlations conform to established geomechanical principles and have been previously substantiated in peer-reviewed literature that deals with identical lithologies.

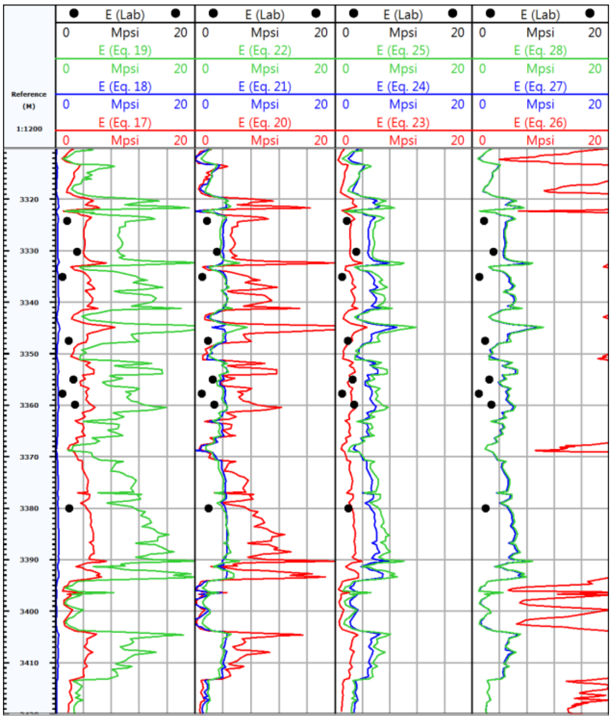

Fig. 3. Shows the static Young's modulus correlations against the core data

This technique evaluates the stiffness of the rock and its capacity to withstand pressure. A threshold of 0.42×10^{12} psi^2 was established, indicating that values below this critical limit pose a high risk of sand production, as shown in the first track of Fig. 4. Additionally, the compressional sonic wave (CSW) is the fourth technique utilized in this study. It measures the propagation of sound through the rock. A threshold of 80 µs/ft was identified (as shown in the second track of Fig. 4); if the CSW value exceeds 80 µs/ft, the rock is considered weak and susceptible to sanding, whereas lower values indicate stability.

Finally, the profiles of the B-index (Eq. (30)), S-index (Eq. (31)), and Ec-index (Eq. (32)) techniques were constructed, as shown in Fig. 4. All seven threshold criteria, i.e., *CSW*, *UCS*, *PHIT*, G/C_b, *B*-index, *S*-index, and E_c-index, have effectively identified intervals at various depths (e.g., 3312, 3318, 3322, 3368-3370, 3394-3396, and 3398 m MD) that pose a risk of sand production in the upper sandstone stratum of the Zubair reservoir. Therefore, these intervals should be taken into account during workover activities to mitigate challenges related to sand formation. In other words, it is essential to consider these intervals when implementing the perforation jobs to prevent issues with sand production.

The threshold limit for sanding risk associated with each of these methods is inserted in Table 3. The discrepancies in most of the threshold limits presented in Table 3 compared to those previously reported in the literature arise from modifications made to align them with the thresholds pertinent to this field of investigation. Additionally, the threshold techniques mentioned were developed using specific reservoir data, which results in discrepancies due to variations in reservoir characteristics, types and quantities of fluid content, and lithology.

Table 3. Critical limits for predicting the onset of sand production

Method	Critical limit of onset of sanding	Unit
UCS	< 4200	psi
PHIT	> 0.2	v/v
G/C_b	< 0.42 x 10^{12}	psi^2
CSW	> 80	µs/ft
B-index	< 1.6 × 10^6	psi
S-index	< 9.2 × 10^9	psi
E_c-index	< 0.35 x 10^6	psi

The derived sanding initiation thresholds indicate the onset of sand production and are directly associated with measurable physical and mechanical properties of rock, including unconfined compressive strength (UCS), tensile strength, porosity, and Poisson's ratio. Moreover, field development planning can effectively utilize these thresholds to enhance production strategies. By comprehending the safe drawdown limits based on rock failure criteria, operators can proactively design sand control systems, select completion strategies, and establish safe production limits to minimize formation failure and sand influx. Finally, the correlations used to predict the onset of sand production are inherently specific to various sandstone formations; however, the threshold values derived from these correlations are unique to each formation. Variations in mineral composition, cementation, stress conditions, and pore pressure necessitate recalibrating the correlations before applying them to other reservoirs. Without such calibration, utilizing these thresholds could lead to either an underestimation or overestimation of sanding risks.

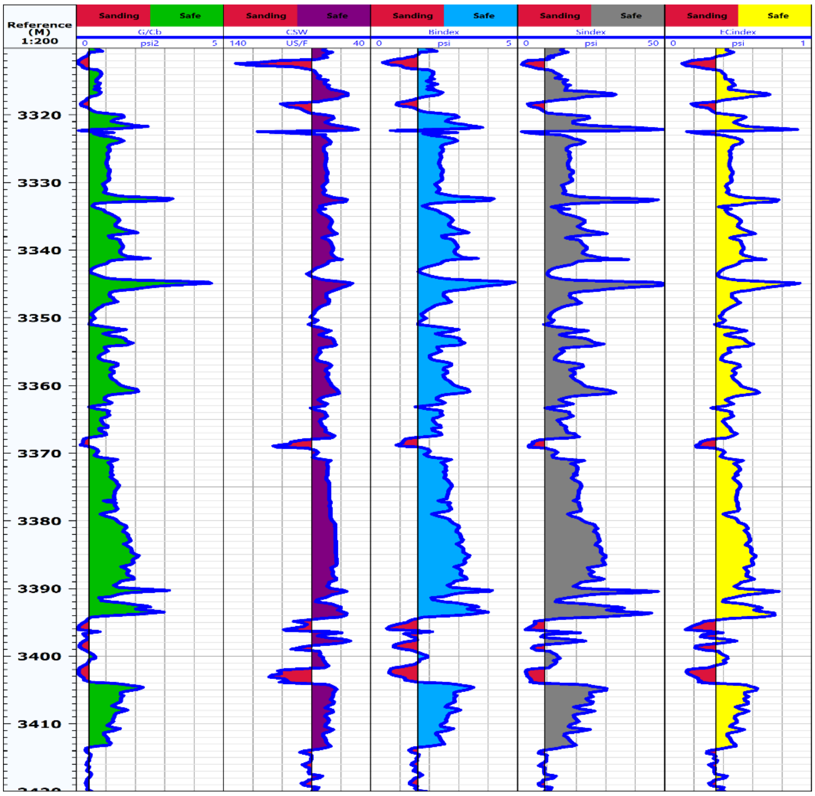

Fig. 4. Illustrates the threshold limit for predictive techniques

IV. Conclusions

The current study was conducted in an oilfield in southern Iraq to address the issue of sand production. It provises a reliable indicator for predicting sand production throughout the well's lifetime and assists production engineers in determining and designing the appropriate completion type to reduce sanding problems. The subsequent points summarize the conclusions of the study:

- This study used seven methodologies to determine sanding prediction intervals: *UCS*, *PHIT*, *CSW*, G/C_b, *B*-index, *S*-index, and Ec-index. Each method contributes to assessing rock formation stability and identifying critical parameters influencing sand production.
- Sand production is probable when the diminishing values of G/C_b (< 0.42×10^{12} psi^2), *UCS* (< 4200 psi), *B*-index (< 1.6×10^6 psi), *S*-index (< 9.2×10^9 psi), and E_c-index (< 0.35×10^6 psi) drop below their essential thresholds, while the rising values of *PHIT* (> 0.2) and *CSW* (> 80 µs/ft) surpass their respective critical limitations.
- The computed threshold values should be used to define secure operating intervals in production planning. Additionally, when data is insufficient, log-based correlations provide a viable method for accurately determining sanding thresholds.
- In rocks characterized by increased porosity and decreased unconfined compressive strength, sanding is likely to occur over time, even under moderate drawdowns. In such cases, engineers should emphasize the use of the UCS index alongside acoustic log responses to evaluate sanding risk.
- Finally, the results of this study are applicable to the oil fields in the south of Iraq. However, for implementation in different areas, calibration with offset well data is essential to guarantee ensure accuracy.

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