Determining the Magnitudes of Maximum and Minimum Horizontal Stresses from Borehole Data: Comparison Between Borehole Failure Approach and Poroelastic Strain Model

Nazir Mafakheri Bashmagh
Kyoto University, Kyoto, Japan

Weiren Lin
Kyoto University, Kyoto, Japan

Abbas Khaksar Manshad
Petroleum University of Technology, Abadan, Iran

ABSTRACT: This paper compares the magnitudes of horizontal stresses estimated by the poroelastic horizontal strain model and borehole breakout approaches in one of the oil wells near the Zagros suture zone. First, the poroelastic horizontal strain model was utilized for determining the magnitude of maximum horizontal stresses, using vertical stress, pore pressure, and physical properties of the rock determined based on wireline logs. Then, the breakout approach was employed to determine the magnitude of horizontal stresses. The R^2 of the linear regression between the two methods for minimum and maximum horizontal stress was 0.74 and 0.71, respectively. Even though there are different correlations in some depths, the consistency is generally significant, and stress regimes in both methods were consistent in almost all intervals. The results show this method's capability to calibrate the poroelastic strain method using the breakout approach continuously.

Keywords: Rock failure, In situ stress, poroelastic strain model, Borehole compressive failure.

1 INTRODUCTION

Knowledge of the in-situ stress is essential for wellbore stability analysis, hydraulic fracturing in the upstream petroleum industry (Heidbach et al., 2018; Lin et al., 2010; Radwan et al., 2021; Tingay et al., 2005; Zoback, 2007). The in-situ stresses are conventionally defined by three principal components in vertical and horizontal directions: vertical stress (S_V), minimum horizontal stress (Sh), and maximum horizontal stress (S_H) (Fjær et al., 2008). Estimating S_H has long been recognized as the most challenging component of the stress tensor to estimate accurately. Since most of the direct methods that provide reliable information about S_h are very costly and time-consuming, indirect methods based on empirical correlation have been proposed to estimate in-situ stress. Among these direct and indirect techniques, the rock failure approach, well measurements, and empirical equations are among the most popular methods (Lin et al., 2011; Mafakheri et al., 2021; Najibi et al., 2017). Accordingly, indirect methods based on empirical correlation, such as the poroelastic horizontal strain model and breakout approaches, have been proposed to estimate in-situ stresses (Fjær et al., 2008; Zoback et al., 1985). However, since verifying these empirical equations is challenging, a validation with conventional borehole wall compressive failure phenomenon called borehole breakout was evaluated. This paper aims to compare two approaches for determining the magnitude of S_H and S_h, although the data has been utilized to characterize tectonic stress in the Zagros suture zone (Mafakheri et al., 2022). Compared to the borehole breakout method, the poroelastic horizontal strain model is easier to implement, and the time consumption is lower. Therefore, calibration by breakout will be valuable.

2 METHODOLOGY

This study used conventional and borehole image logs to determine the magnitudes of in-situ principal stresses. Several breakouts were detected along 1600 m and 2000 m. Two approaches were applied and compared to ensure the accuracy of the results. Initially, vertical stress was calculated as follows:

$$S_v = \int_0^H RHOB * g \, dH \tag{1}$$

2.1 *Breakout method*

In the first approach, breakout features, such as width and height, combined with physical properties and caliper, were used to determine the magnitude of horizontal in situ stresses. Finally, the breakout approach determined horizontal stresses using Zoback et al. (1985). This method's horizontal stresses depend on the borehole shape deformation caused by wellbore failure and the rock's physical properties:

$$S_{H(BO)} = \frac{2[(d_1 + d_2)(S_c - e\Delta P) - (b_1 + b_2)(S_c - f\Delta P)]}{[(a_1 + a_2)(d_1 + d_2) - (b_1 + b_2)(c_1 + c_2)]} \tag{2}$$

$$S_{h(BO)} = \frac{2[(a_1 + a_2)(S_c - f\Delta P) - (c_1 + c_2)(S_c - e\Delta P)]}{[(a_1 + a_2)(d_1 + d_2) - (b_1 + b_2)(c_1 + c_2)]} \tag{3}$$

$S_{H(BO)}$ is the maximum horizontal stress, and $S_{h(BO)}$ is the minimum. The variables a_1, a_2, b_1, b_2, c_1, c_2, d_1, d_2, e, and f depend on several parameters such as coefficient of friction (μ), angle of breakout initiation with respect to the maximum horizontal stress (θ_b), depth of breakout initiation (r_b), azimuth between the direction of the maximum horizontal principal stress and the breakout region (θ), the radius of the well (a), and the difference (ΔP) between the borehole fluid pressure and formation pressure. In this study, borehole fluid pressure was determined based on the actual hydrostatic pressure of the mud column in the wellbore, and the formation pressure was determined directly by the extrapolation of pressure from RFT test points.

2.2 *Poroelastic Horizontal Strain method*

The second approach is the poroelastic horizontal strain theory method. In this method, horizontal stresses were determined using pore pressure, vertical stress, and the physical properties of the rock. The poroelastic horizontal strain model, presented by Fjaer et al. (2008), considers the rock strains to determine anisotropic horizontal stresses. This approach has been used frequently to determine principal in-situ stresses (Amiri et al., 2019; Baouche et al., 2020). The maximum horizontal stresses $S_{H(PES)}$ and minimum horizontal stresses $S_{h(PES)}$ are as follows:

$$S_{h(PES)} = \frac{\upsilon}{1-\upsilon}\left(S_v - \alpha P_p\right) + \alpha P_p + \upsilon_s \frac{E_s}{1-\upsilon^2}\varepsilon_x + \frac{E_s}{1-\upsilon^2}\varepsilon_y \tag{4}$$

$$S_{H(PES)} = \frac{\upsilon}{1-\upsilon}\left(S_v - \alpha P_p\right) + \alpha P_p + \upsilon \frac{E_s}{1-\upsilon^2}\varepsilon_y + \frac{E_s}{1-\upsilon^2}\varepsilon_x \quad (5)$$

$$\varepsilon_x = S_v \frac{\upsilon}{Es}\left(\frac{1}{1-\upsilon} - 1\right) \quad (6)$$

$$\varepsilon_y = S_v \frac{\upsilon}{Es\left(1 - \frac{\upsilon^2}{1-\upsilon}\right)} \quad (7)$$

Where the vertical in-situ stress (overburden pressure) is S_v, the static Young's modulus (E_s), dynamic Young's modulus (E_d), Poisson's ratio (υ), ε_x and ε_y are the strains in the S_H and S_h directions, respectively. Eventually, the findings of both approaches will be discussed in the subsequent section.

3 RESULTS AND DISCUSSION

In this section, the aforementioned empirical correlations introduced in previous sections will be used in the case study to show their application in accurately estimating horizontal stresses. The magnitudes of principal in-situ stresses, including vertical stress and the maximum and minimum horizontal stresses, were determined, and plotted in Figure 1a. In this study, overall, 52 distinct

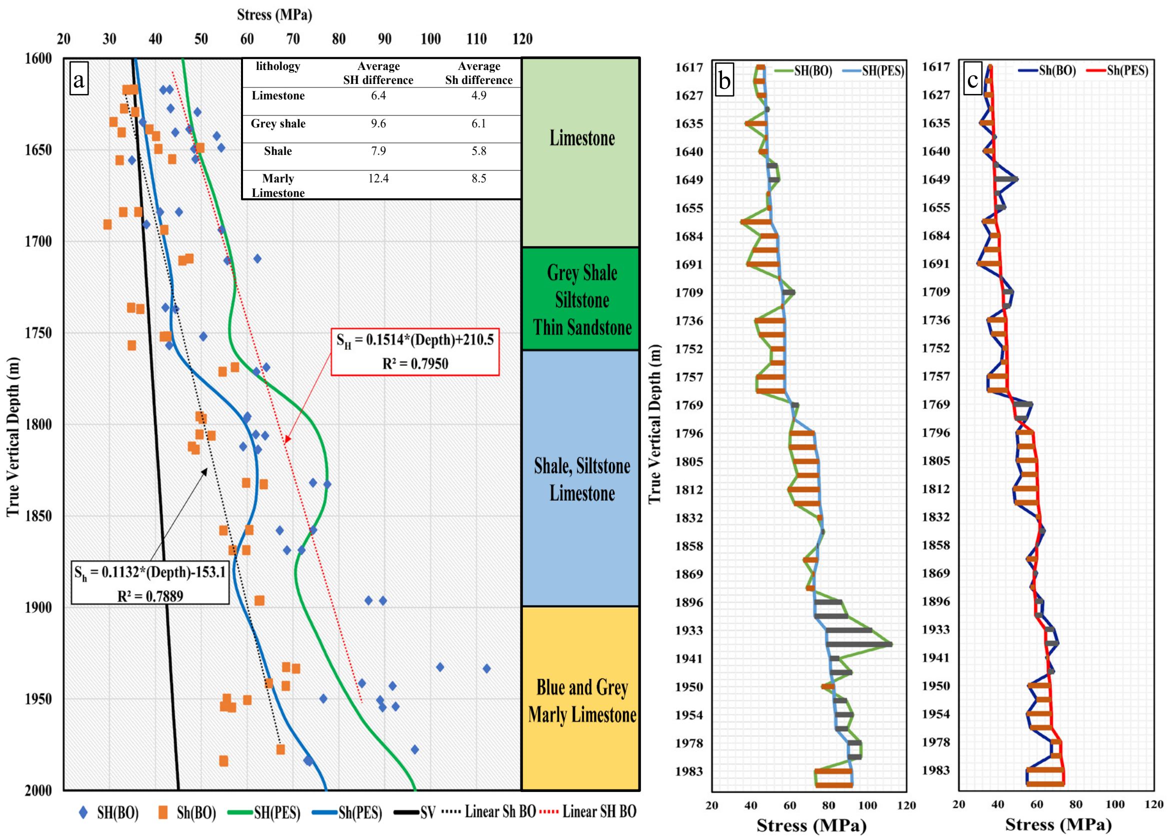

Figure 1. a) Magnitude of principal in situ stresses including vertical stress, minimum and maximum horizontal stresses for both approaches. b, c) Comparison of maximum horizontal stress based on both approaches. Up/down bars indicate the differences between the results. Orange bars indicate that horizontal stress derived from Poroelastic strain theory is greater than breakout method and grey bars show the opposite.

breakouts from 26 pairs of breakout sets were detected. As shown in figure 1a, Linear regression from the breakout analysis approach showed an R-Squared of 0.7950 and 0.7889 for the maximum and minimum horizontal stresses, respectively. In the entire studied interval, the maximum horizontal stress gradient value based on the Poroelastic strain theory is 6.2 MPa/100m gradually. While this number varies from 5.3 to 6.3 MPa/100m for minimum horizontal stress. As presented in Figure 1a and the stress polygon in Figure 2, around a depth of 1600 m, based on both approaches, the vertical stress likely exceeds the minimum horizontal stress, and the stress regime is strike-slip. However, below 1600 m, the dominant stress regime is a reverse (thrust) fault stress regime. Figures 1b and 1c plotted maximum and minimum horizontal stresses from the poroelastic strain versus the breakout method. The up/down bars represent the differences between the two results. For most intervals, there are similarities between the change in up/down bars for both maximum and minimum horizontal stresses. No dramatic differences in the results have been observed.

Ideally, these empirical methods should be calibrated with direct measurements of horizontal stress, such as the leak-off test and mini-frac test. Unfortunately, in this study, such data were not available. However, there were no certain methods for calibrating the results, but calibrating these approaches together would enable us to improve the estimation in future cases. Therefore, the estimated value of horizontal stresses would be more reliable if a good match between the predicted horizontal in situ stresses from the poroelastic strain method and results from the breakout approach in the wellbore were observed. Figure 2 shows this field's stress polygon for four different approximate depths. However, the stress regime based on both methods is significantly consistent, but the data points are more scattered in deeper intervals. This fact opens the door for several hypotheses behind the inconsistencies.

As shown in Figures 1a,b, and c, different depths show variation in average maximum and minimum horizontal differences. On the other hand, the limestone formation in the shallower depths shows the least difference. It probably indicates that the poroelastic strain theory is more consistent

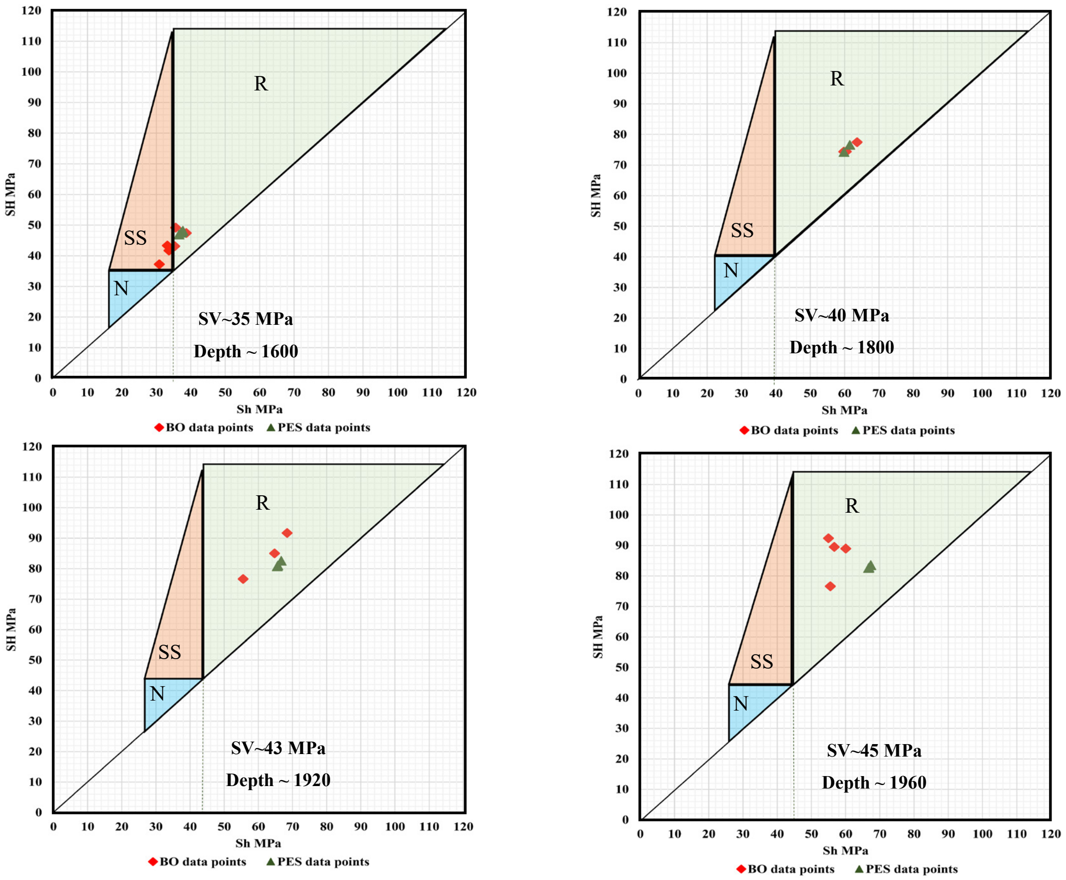

Figure 2. Comparsion between the results of breakout and poroelastic strain mehtod for maximum and minimum horizontal in situ stress by stress polygon.

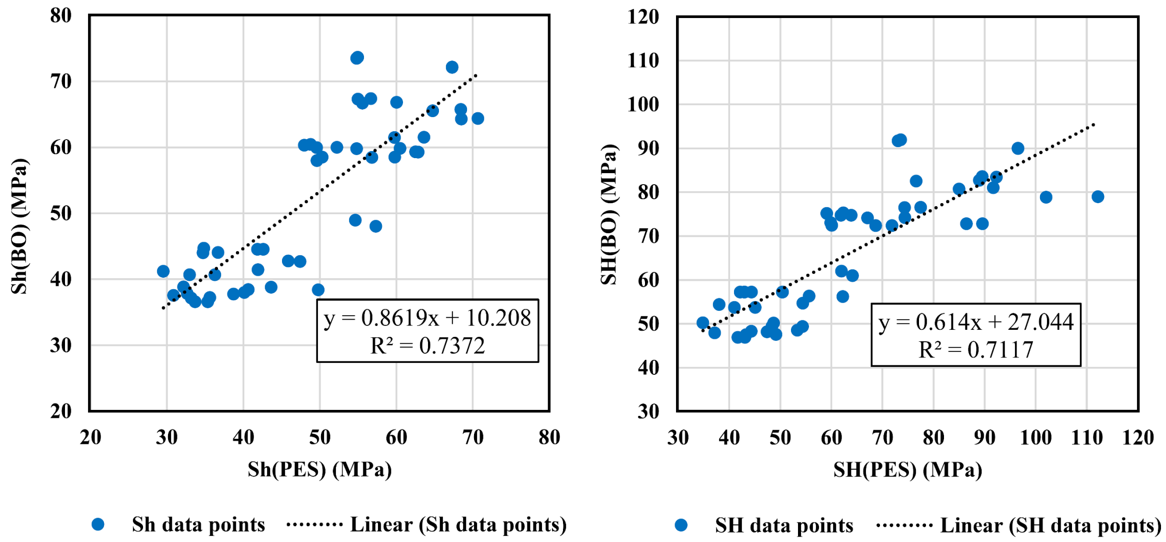

Figure 3. Comarison of the maximum and minimum horizontal stress derived from borehole breakout approach and poroelastic strain method.

with the breakout approach in this interval. There are several hypotheses for explaining these differences. First, as mentioned earlier, the average horizontal stress differences generally increase in deeper intervals, and consequently, the calibration would be less reliable. Second, the stress regime affects the consistency of results. For example, the intervals with a strike-slip regime show a lower difference, and the reverse fault regime reveals a higher difference. Third, the lithology and physical properties of rock influence the differences between the results of the two methods. For example, pure limestone shows the lowest differences, and formations with higher clay content indicate relatively greater differences. It is well known that the physical properties of rock, such as rock strength, young module, and friction angle, play an important role in the mechanism of borehole breakout occurrence and make a greater difference in the results. Besides, in Equations 2 and 3, the accuracy of the depth of breakout initiation (r_b) greatly impacts the results of the horizontal stresses. Finally, the results could be misinterpreted since the mud cake thickness on the breakout surface is associated with lithology. Even though these hypotheses stand on a reasonable pillar, there are some counterexamples in some depths. For instance, based on the first hypothesis, the average horizontal stress differences in Figure 1a, the shale-siltstone-limestone formation should have a higher difference than the grey shale formation, but the results are the opposite. In reality, a combination of mentioned reasons probably caused the differences between the two methods.

In the last step, the comparison was conducted between two sets of results in order to calibrate the poroelastic strain results with the breakout approach. As shown in figure 3, the minimum horizontal stress derived from the borehole breakout approach and poroelastic strain method has a slightly higher correlation than the maximum horizontal stress. The R-squared value for minimum and maximum horizontal stress is 0.73 and 0.71, respectively. Eventually, the following equations are suggested to calibrate the horizontal stresses based on the Poroelastic strain method:

$$S_{h(PES)}{}^{*} = 0.86 S_{h(PES)} + 27 \tag{8}$$

$$S_{H(PES)}{}^{*} = 0.61 S_{H(PES)} + 10.2 \tag{9}$$

Where $S_{H(PES)}{}^{*}$ is calibrated maximum horizontal stress and $S_{h(PES)}{}^{*}$ is calibrated minimum horizontal stress.

4 CONCLUSION

Predicting wellbore stability based on stress field determination is one of the most difficult tasks during the drilling. There were several methods for estimating horizontal in-situ stresses, and two of them were presented briefly in this study. This paper attempted to compare and calibrate the application of these different approaches through a case study from northeast Iraq. The results indicated that maximum and minimum horizontal stress, determined by the poroelastic strain method, could be calibrated by empirical breakout approaches. The breakout approach method was also found to be a more sophisticated approach.

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