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A novel approach to estimate rock strength parameters from multistage triaxial tests (the A-HAS method)

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ABSTRACT

Rock strength parameters are vital to creating robust geomechanical models for wellbore stability, sand production, and hydraulic fracturing. Static rock strength parameters can be estimated from single stage triaxial tests (SST) or multistage triaxial tests (MST). Although SST tests are the most accurate way to estimate rock strength parameters, SST tests require at least four to five core plugs to estimate rock strength parameters. Thus, MST tests are used as an alternative method to estimate rock strength parameters from only one core plug to overcome the limitation of materials and save time and money. However, the currently used method to estimate rock strength parameters is the yield-based only method which can significantly underestimate rock strength (especially unconfined compressive strength (*UCS*)) and can hinder creating a robust geomechanical model. In this work, the authors proposed a novel method called the A-HAS method which is a correction to the yield-based method that is currently used. Using core plugs from three different zones (Nahr Umr shale, Zubair shale, and Zubair sandstone in the Rumaila field, Iraq), SST and MST tests were executed. Rock strength parameters were estimated based on SST tests for each zone (Base Case). Then, rock strength parameters were estimated based on four different methods; the currently used yield-based only method (Case 1) from MST, corrected maximum compressive strength (*MCS*) (Case 2 or the A-HAS method) from MST, and Cases 3 and 4 which are based on corrections from both SST and MST tests. The results have shown that regardless of the method used, coefficient of friction (μ_i) and internal friction angle (ϕ) were not significantly affected while *UCS* and cohesive strength (S_o) were highly affected. Comparing *UCS* and S_o results of the yield-based method (Case 1) and the A-HAS method (Case 2) to the Base Case, the A-HAS method has significantly outperformed the yield-based method in all three zones tested. The A-HAS method has resulted in errors of 4%, 3%, and 2% for Nahr Umr shale, Zubair shale, and Zubair sandstone, respectively while the yield-based method resulted in errors of 41%, 31%, 83% for Nahr Umr shale, Zubair shale, and Zubair sandstone, respectively. The error of the yield-based method is very significant and may hinder creating robust geomechanical models for wellbore stability, sand production, hydraulic fracturing, and many other applications. The authors recommend utilizing the novel A-HAS method to obtain rock strength parameters (especially *UCS* and S_o) from MST tests and not utilize the currently used yield-based method since the A-HAS has proven to be effective and produced better results in the three tested zones than the yield-based method. By using the A-HAS method, the limitations of the MST tests can be overcome and reliable results from MST tests can be achieved which will contribute to saving time, money, and material.

Author credit

Abo Taleb T. Al-Hameedi: Conceptualization, Methodology, Discussion, and Writing- Original draft. **Husam H. Alkinani:** Conceptualization, Methodology, Discussion, Results Analysis, Conceptualization, and Writing- Reviewing and Editing. **Shari Dunn-Norman:** Supervision and Project administration. **Munir Aldin:** Experimental Work, Methodology, and Validation. **Sudarshan Govindarajan**:

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Experimental Work, Methodology, and Validation.

1. Introduction

Wellbore stability analysis relies on the understanding of rock mechanical properties, wellbore trajectory, and mud weight design (Zhang et al., 2018). Shear and tensile failures are the two major types of wellbore failures that cause instabilities in the wellbore during drilling (Chen et al., 2018). The instability of wellbore problems incurs the drilling companies' millions of dollars in additional annual spending (Li et al., 2018; Wang et al., 2019). In order to improve the drilling efficiency, more in-depth studies of the wellbore stability issues are crucial (Abbas et al., 2018a). The in-situ stress equilibrium around the borehole gets disturbed as soon as the drilling bit cuts and remove the solid rock and replace it with drilling fluids. This stress disturbance will result in a concentration of stress around the borehole walls (Al Dushaishi et al., 2018; Kamel et al., 2018). At this point, a failure of the wellbore may be anticipated to start. For instance, in the case of overall drilling mud hydrostatic pressure is less than the permeable formation pore pressure, the fluids from the formation will enter the well and contaminate the drilling fluids and if it is not handled properly, a well control situation can occur which may lead to a blowout in severe cases. Besides, when the hydrostatic pressure exerted by the drilling fluids is lower than the breakout pressure of the formation, a collapse failure can occur as a result of the lack of borehole wall support by the mud weight. Thus, the magnitude of the pore pressure dictates the minimum required drilling mud weight to maintain safe drilling and avoid kick or blowout issues. Also, the breakout pressure of the formation (i.e., the collapse pressure) represents the minimum required drilling mud weight to avoid collapse during penetrating the formations. On the contrary, if the drilling mud hydrostatic pressure is greater than the minimum horizontal stress magnitude, tensile will be the dominant condition in this case. Tensile failure can cause reactivation of pre-existing fractures in rocks which can lead to the loss of drilling fluid. In the same way, when the hydrostatic pressure of drilling mud is greater than formation breakdown pressure, the intact rock will be subjected to a tensile failure that leads to drilling-induced fractures in the borehole wall (Abbas et al., 2019).

The stability analysis of the wellbore is usually used to estimate the suitable drilling mud density that is required to stabilize the wellbore. Geomechanical studies aim to utilize and integrate all the obtained data into a mechanical earth model (1D model). Obtained data such as rock strength, pore pressure, elastic properties, induced stress, and in-situ stresses are then matched with a suitable criterion of rock strength to determine the lower limit of drilling mud density that is desired to conduct safe and stable drilling operations (Gholami et al., 2015). Therefore, the understanding and the knowledge of rigorous rock strength parameters are substantial for estimating and analyzing in-situ stresses, wellbore stability, reservoir characterization, sand production, design of hydraulic fracturing, and many other geomechanical applications (Khaksar et al., 2009). Thus, finding an accurate and cost-effective approach for estimating the rock strength parameters is such a big deal, which will contribute to minizine the cost, non-productive time, and the limitations of the rock samples availability, particularly in the deep, overburden, and shale formations.

"Rock strength parameters, such as unconfined compressive strength (*UCS*), cohesive strength (S_o), and internal friction angle (ϕ), indicate the ability of the rock formation to withstand the in situ stress environment around the wellbore. The *UCS* and ϕ are the most commonly used rock strength properties for reservoir geomechanical modeling" (Abbas et al., 2019). Two approaches are normally utilized to estimating rock strength parameters, the first one is related to executing geomechanical lab tests on rock samples (static approach) while the second approach is utilizing empirical correlations derived from wirelines measurements (dynamic approach). For the static approach, two ways are normally implemented to estimate the parameters of rock strength. The first and typical lab test is single stage triaxial tests (SST). SST test is normally conducted for at least four or five core plugs with various values of the confining pressure to construct a relationship among the axial load (σ_1) (to simulate the vertical stress) and the confining pressure (σ_3) (to simulate the horizontal stresses), then graphical plots based on σ_1 vs. σ_3 or p/q plots will be employed to estimate rock strength parameters. It is important to mention that SST represents the most accurate approach for obtaining the parameters of rock strength. However, the SST test is not always feasible to be conducted in the lab since it requires multiple rock samples, and the availability of the rock samples is considered a big obstacle in the oil and gas industry. Therefore, multistage triaxial tests (MST) are usually utilized as an alternative approach to SST tests when there is a shortage of rock samples. In MST tests, only one rock sample will be needed to carry out multi-stages (at least four or five stages), thus solving the core sample scarcity issues. Generally, the accuracy of MST at obtaining rock strength parameters is less when comparing it to SST. For MST procedure, a low value of the confining pressure is normally established on the first stage, and the axial load will be maximized until the point of positive dilatancy is reached (the first yield point), then both the σ_1 and σ_3 at this condition will be obtained for the first stage. For the second stage, the confining pressure will be raised to a new predetermined value and it will be greater than the confining pressure for the first stage, then the axial load will be increased to achieve the second yield point, which is greater than the yield point in the first stage. For the second stage, σ_1 and σ_3 will be reported as well. The same steps will be repeated for the other required stages to obtain yield points along with acquiring the values of σ_1 and σ_3. At the final stage, the test will continue to achieve the maximum compressive strength (*MCS*) by increasing the axial load until failure occurs (Aadnøy and Looyeh, 2019; Fjær et al., 2008; Khaksar et al., 2009; Zoback, 2007).

It has been long known that SST is the most typical and accurate approach regarding obtaining the rock strength parameters; while the MST approach is less reliable than SST, where MST underestimates the rock strength parameters, and that will negatively affect the accuracy and robustness of the 1D geomechanical model. However, MST is still an acceptable technique to be employed to provide the required strength inputs for the ID geomechanical model, where MST provides a better estimation for *UCS*, ϕ, and S_o as compared to the dynamic approach. The main issue with MST tests is that the points of the yield strength (i.e., the points of the positive dilatancy), normally obtained from implementing multistage loads on one rock sample, are used to acquire rock strength parameters. The yield strength values obtained at each stage of MST (i.e., the points of the positive dilatancy) are directly utilized to acquire σ_1 when plotting σ_1 vs. σ_3 without any correction. This practice is very common in the literature to estimate rock strength parameters from MST tests (Aadnøy and Looyeh, 2019; Abbas et al., 2018b; Fjær et al., 2008; Khaksar et al., 2009; Zoback, 2007). That is one reason that MST tests underestimate rock strength parameters compared with SST tests.

Therefore, the ultimate objective of this research is to establish a novel approach to correct yield strength acquired at each stage of MST to a *MCS* that is closer to the *MCS* obtained from SST tests in order to maximize the accuracy of rock strength parameters. This, in return, will contribute to boosting the robustness of the 1D geomechanical model, as well as introducing a new technique to estimate *UCS*, S_o, and ϕ from MST instead of SST in case of having only MST lab data. This novel study has been deduced according to a comprehensive experimental work conducted on various rock samples obtained from three zones (Nahr Umr shale, Zubair shale, and Zubair sandstone in the Rumaila field, Iraq).

2. Materials and methods

2.1. Cores samples

To conduct this experimental study, core plugs were acquired from three zones (Nahr Umr shale, Zubair shale, and Zubair sandstone) located in the Rumaila field, south Iraq. The Rumaila field is recognized

as the third-biggest oil field in the world. The Nahr Umr shale formation is located in the production hole and is considered as one of the most troublesome zones in the Rumaila field during the drilling operations. The drilling issues in this formation are including but not limited to; swelling, sloughing, tight hole, and mechanical stuck pipe. The top of this formation is found roughly between 2720 and 2730 m and the bottom is found approximately roughly 2990–3005 m, which is generally 270–275 m thick. The shale of the Nahr Umr zone is greenish gray, black, sub blocky, occasionally fissile, and slightly calcareous cement. The Zubair formation is a productive zone and it is renowned as one of the most pivotal target formations in Iraq. The top of this formation is found approximately between 3090 and 3100 m and the bottom is found approximately between 3515 and 3535 m, which is generally 425–435 m thick. This formation involves two major layers, which are shale and sandstone. Zubair shale is dark gray, greenish-black, firm, sub fissile, sub blocky, slightly calcareous cement, splintery, and occasionally thinly banded with dark gray claystone. While Zubair sandstone is quartz, transparent to translucent, firm, friable in places very fine to fine grain, sub-rounded, sub-spherical, well-sorted, glassy, luster, good visible porosity, and good inferred permeability. Penetrating boreholes in the Zubair formation has normally been a challenge due to the weak nature of the shale sequence as well as the wellbore instabilities in both the sandstone and the shale sequences. Drilling issues in the Zubair formation are, including but not limited to; differential and mechanical stuck pipes, swelling, sloughing, and tight hole. Fig. 1, Fig. 2, and Fig. 3 show the core plugs before and after implementing SST and MST tests for Nahr Umr shale, Zubair shale, and Zubair sandstone, respectively (Al-Hameedi et al., 2017; Basra Oil Company, 2010; Jassim and Goff, 2006).

2.2. Core samples preparation

The core plugs used in this work were 10 times wider than the largest rock grain and the length of each plug is at least 2 times the diameter. To ensure a flat surface right angle, samples ends were surface ground. Also, accurate measurements of diameter, length, and weight for each sample being tested were recorded.

2.3. Single stage triaxial tests (SST)

This test is usually utilized to precisely estimate the mechanical rock properties. It can be used to obtaining elastic moduli such as shear modulus (G_s), Young modulus (E_s), bulk modulus (K_s), and Poisson's ratio (v_s) by investing one rock plug. However, to obtain rock strength, four or five core plugs will at least be needed to conduct SST on each one separately, and that may be an issue in case there are limitations related to material availability and time (Abbas et al., 2018a; Ameen et al., 2009; Fjær et al., 2008; Zoback, 2007). Therefore, for this study, SST tests were executed on rock plugs from three various zones (Nahr Umr shale, Zubair shale, and Zubair sandstone) to obtain rock strength parameters. For each core sample, to simulate the horizontal stresses faced in situ by the reservoir, confining pressure was set initially as a constant value throughout the entire duration of SST. Furthermore, the axial stress was maximized until the rock sample reached out the maximum compressive strength (*MCS*) (the point where the sample failure occurs). It is crucial to point out that the set value of the confining pressure was not chosen randomly, where it was selected according to the real field data of the horizontal stresses in these cored formations. Furthermore, a computerized digital data acquisition system was employed to record axial and radial deformation, axial load, and confining pressure (Alsalman et al., 2015). Fig. 4 shows the rock mechanics testing system used in this work.

2.4. Multistage triaxial tests (MST)

This method is normally invested to be executed on one core plug to obtain rock strength parameters (S_o, ϕ, and *UCS*) with decent accuracy. It helps to avoid the limitations that are usually associated with the availability of the rock samples and the issue of time. Nevertheless, the accuracy is less when comparing it to the SST approach (Abbas et al., 2018a; Fjær et al., 2008; Zoback, 2007). Rock samples were obtained from three different layers (Nahr Umr shale, Zubair shale, and Zubair sandstone), and MST tests were conducted on the core samples to acquire rock strength parameters. Then, the findings of the MST tests were compared and verified to the findings of the SST tests in order to establish a novel technique regarding maximizing the accuracy of the rock strength parameters obtained from MST tests. The rock sample was put in a triaxial cell and it was loaded axially by axial load and radially by confining pressure. For MST tests, confining pressure will be set for each stage of MST, and those values will be selected according to the real field data of the horizontal stresses in the cored zones. Four stages were conducted on each rock sample, where the confining pressures were different for each stage. For the first stage of MST, the axial load is raised till accomplishing the yield point (transition point from elastic to plastic deformation) with the set confining pressure, and similar procedures were repeated for other stages by raising confining pressure for every stage along with the axial load. It is crucial to mention that the

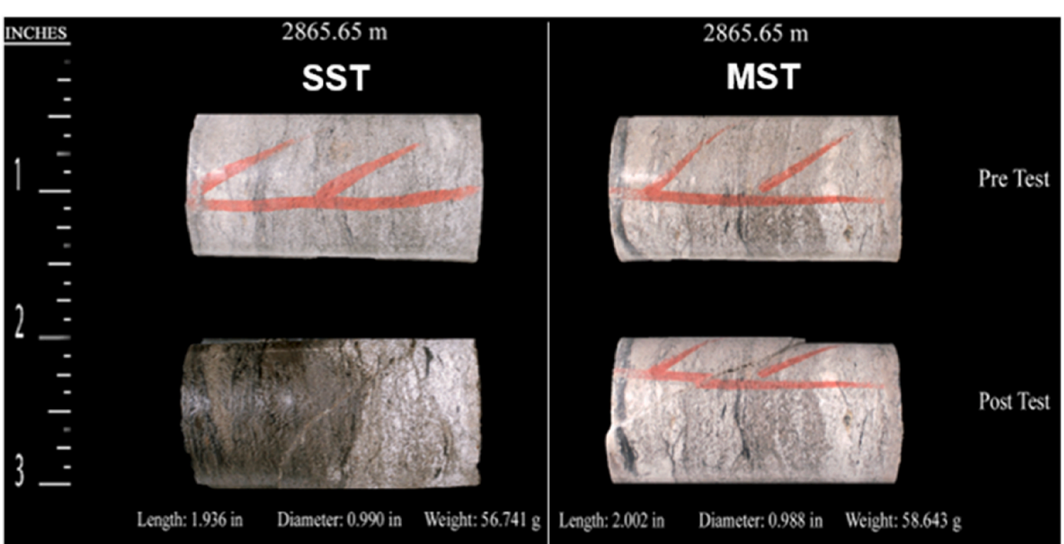

Fig. 1. Nahr Umr rock sample pre and post test.

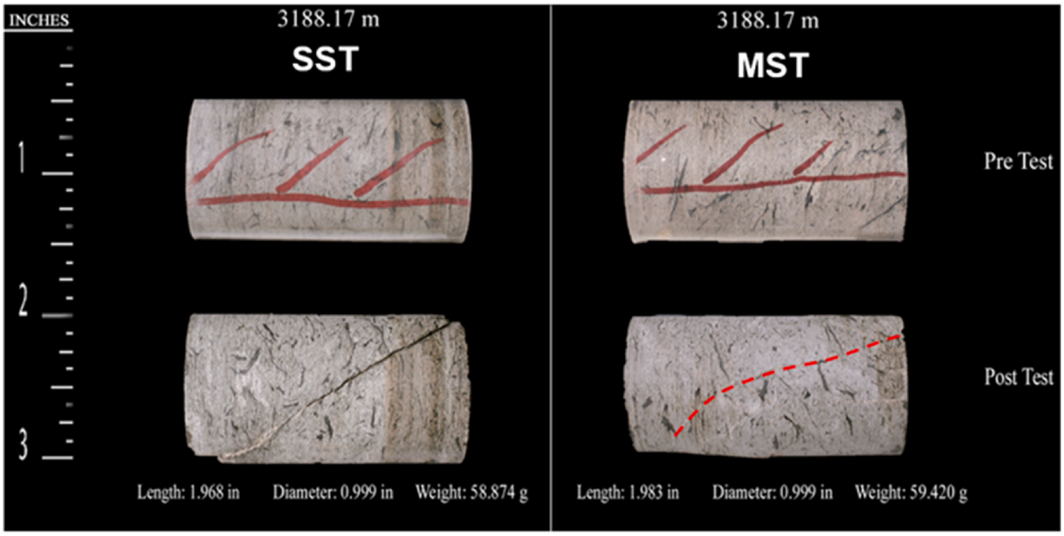

Fig. 2. Zubair shale rock sample pre and post test.

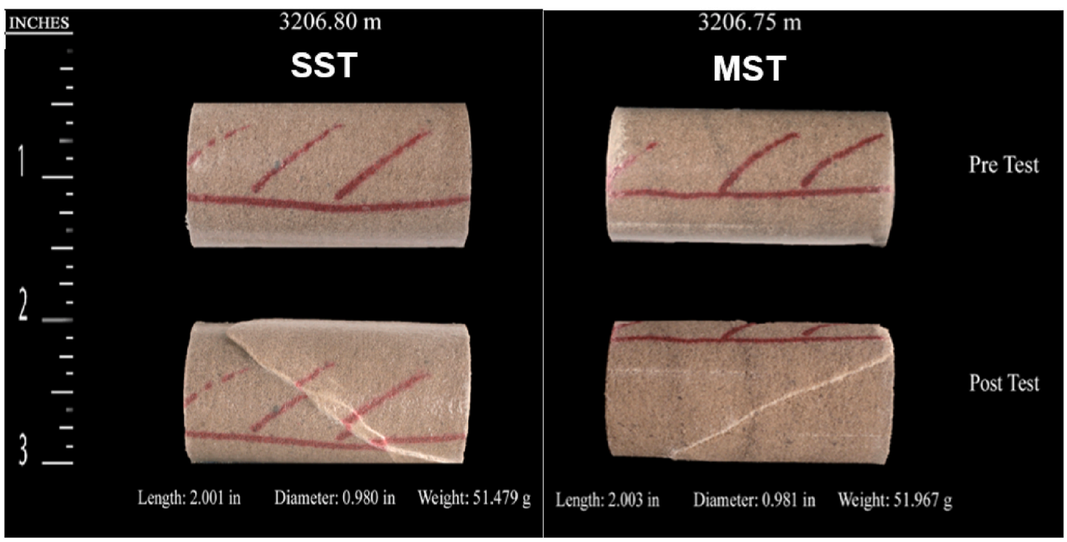

Fig. 3. Zubair sandstone rock sample pre and post test.

maximum compressive strength (*MCS*) was obtained in the last stage by increasing the axial load until the sample's failure occurred. Finally, all the tests were controlled by a computer that connected to all data acquisition systems to monitor and report all the data of the MST (e.g., axial and radial deformations, axial load, and confining pressure) (Alsalman et al., 2015).

2.5. Estimation of rock strength parameters

A reliable estimation of rock strength parameters is a pivotal key for achieving a rigorous and accurate analysis for rock mechanics applications, including but not limited to; wellbore stability, sand control, hydraulic fracturing design, reservoir characterization, fault reactivation, etc. Unconfined compressive strength (*UCS*), cohesive strength (S_o), internal friction angle (ϕ), and coefficient of friction (μ_i) are the main components of rock strength parameters. However, *UCS* and ϕ are the only two parameters of rock strength that are typically required to be utilized as inputs for the geomechanical models and their applications (Aadnøy and Looyeh, 2019; Abbas et al., 2018a; Fjær et al., 2008; Khaksar et al., 2009; Zoback, 2007). Therefore, this sub-section will highlight the graphical methods that are commonly utilized to estimate the parameters of rock strength.

Starting with the first graphical method, which is simply by plotting σ_1 vs. σ_3 as shown in Fig. 5, where σ_1 represents the axial load and σ_3 presents the confining pressure. For this plot, *UCS* can directly be obtained from the graph, which represents the y-intercept of the line of a slope of *n*. Nevertheless, μ_i, ϕ, and S_o cannot be estimated directly from the plot, the following equations can be utilized to obtain them (Zoback, 2007):

$$\mu_i = \frac{n-1}{2\sqrt{n}} \quad (1)$$

$$\varphi = \tan^{-1}(\mu_i). \quad (2)$$

$$S_0 = \frac{UCS}{2\left[(\mu_i^2+1)^{1/2} + \mu_i\right]} \quad (3)$$

The second method is using the *p*/*q* plot which is a simplified version of the linearized Mohr-Coulomb plot that allows plotting σ_1 and σ_3 instead of normal and shear stresses as shown in Fig. 6. In the *p*/*q* plot, the intercept of the line is *C*, and the slope of the line is *m*. Based on *C* and

Fig. 4. Rock mechanics testing system.

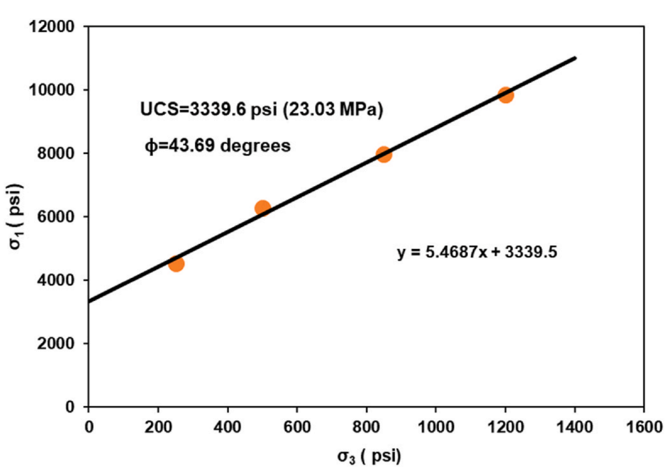

Fig. 5. σ_1 vs. σ_3 plot.

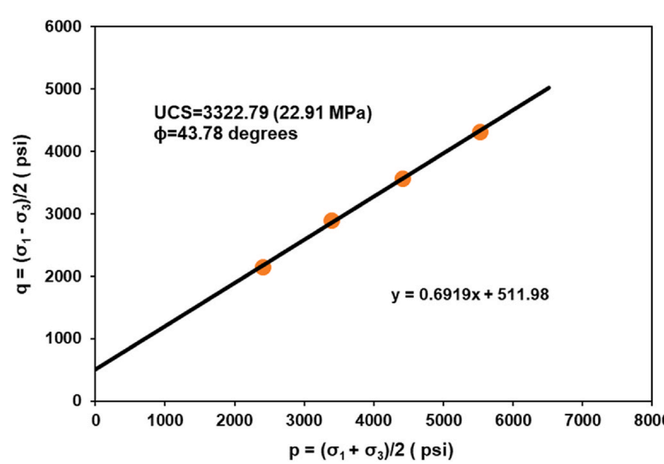

Fig. 6. P/q plot.

m, the following equations can be used to estimate S_0, ϕ, μ_i, and UCS, respectively:

$$S_0 = \frac{C}{\cos\varphi} = \frac{C}{\sqrt{(1-m^2)}} \tag{4}$$

$$\varphi = \sin^{-1}(m) \tag{5}$$

$$\mu_i = \tan(\varphi) \tag{6}$$

$$UCS = 2S_0\left[\left(\mu_i^2+1\right)^{1/2}+\mu i\right] \tag{7}$$

Table 1 shows a summary of the findings of the rock strength parameters for both graphical methods for the same core sample. Based on Table 1, the values of rock strength parameters are almost the same with a negligible difference for both graphical methods (i.e. ~17 psi difference in UCS, 0.09° difference in ϕ). Thus, using any method can provide approximately the same values of rock strength parameters with a negligible difference. In this paper, σ_1 vs. σ_3 will be used to estimate rock strength parameters due to its simplicity.

3. Results and Discussion

In this section, four methods are presented to correct the yield strength (YS) to the maximum compressive strength (MCS) in order to obtain robust rock strength parameters from MST tests. Furthermore, a comparison between the methods will be presented while the SST-based rock strength parameters will be used as a reference for this investigation study (Base Case).

3.1. Base Case: SST-based rock strength parameters

Estimating rock strength parameters based on SST is the most accurate way. It is required to have at least four to five core samples to obtain rock strength parameters from SST. Thus, it is very common to use MST to obtain rock strength parameters based on yield strength only. Nevertheless, SST-based rock strength parameters are the most accurate way to obtain not only rock strength parameters but also elastic properties, as well. This is due to using multiple cores and reaching the MCS in every core plug. Therefore, this method will be selected as the "Base Case" and all results will be compared with the Base Case. Fig. 7, Fig. 8, and Fig. 9 show the results of rock strength parameters from SST based on four core plugs of Nahr Umr shale, Zubair shale, and Zubair sandstone, respectively.

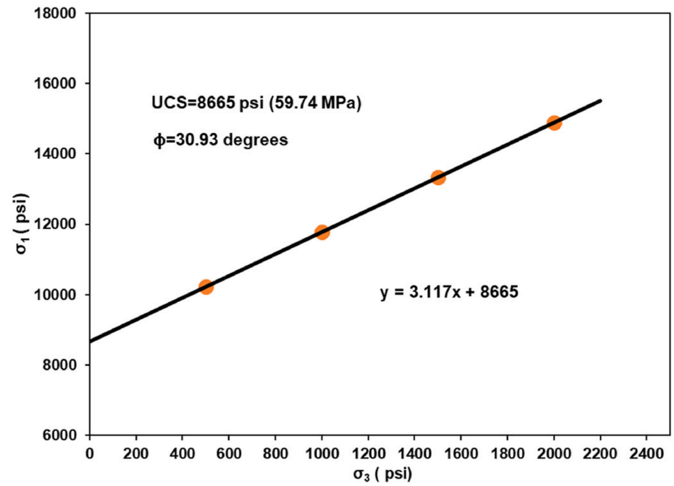

Fig. 7. SST-based rock strength parameters (Nahr Umr shale).

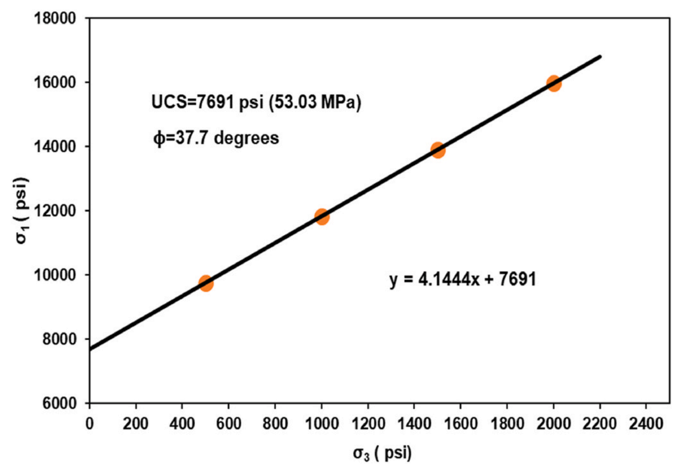

Fig. 8. SST-based rock strength parameters (Zubair shale).

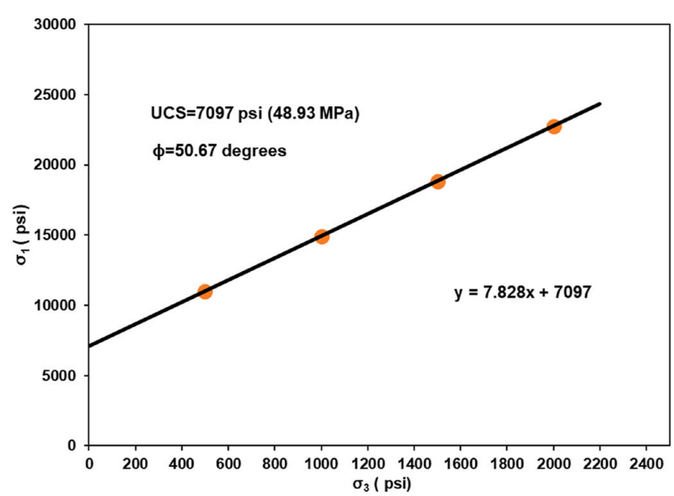

Fig. 9. SST-based rock strength parameters (Zubair sandstone).

3.2. MST-based rock strength parameters

3.2.1. Case 1: yield-based only (no correction)

Yield-based rock strength parameters can be acquired by plotting the yield point at each stage of MST tests with confining pressure (at each stage, σ_1 is obtained from yield point (σ_1 = yield strength + σ_3) and σ_3 is the confining pressure at each stage). This method is the most common method used to obtain rock strength parameters from MST tests based on the literature (Aadnøy and Looyeh, 2019; Abbas et al., 2018b; Fjær et al., 2008; Khaksar et al., 2009; Zoback, 2007). However, this method usually underestimates UCS which can lead to a major error in geomechanical models. Fig. 10, Fig. 11, and Fig. 12 show the σ_1 vs. σ_3 plotted based on Yield-based only for Nahr Umr shale, Zubair shale, and Zubair sandstone, respectively.

Table 1
Summary of the results of graphical methods.

Graphical Method	UCS (psi)	ϕ	μ_i	S_0 (psi)
σ_1 vs. σ_3 plot	3339.6	43.69	0.955	714.27
p/q plot	3322.8	43.78	0.958	709.12

3.2.2. Case 2: corrected MCS-based rock strength parameters (the A-HAS method)

This method is one of the methods proposed in this paper to obtain rock strength parameters. This method accounts for the corrected MCS instead of YS in calculating rock strength parameters (called the A-HAS

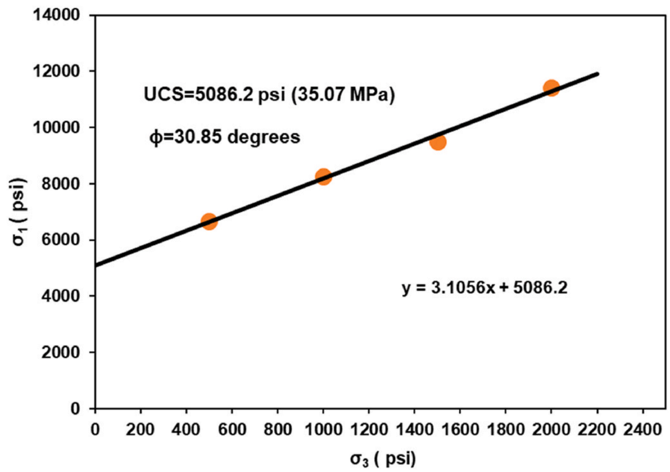

Fig. 10. Yield-based rock strength parameters (Nahr Umr shale).

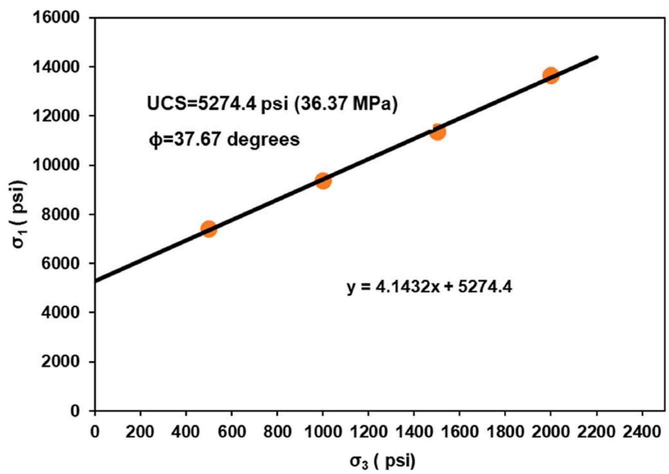

Fig. 11. Yield-based rock strength parameters (Zubair shale).

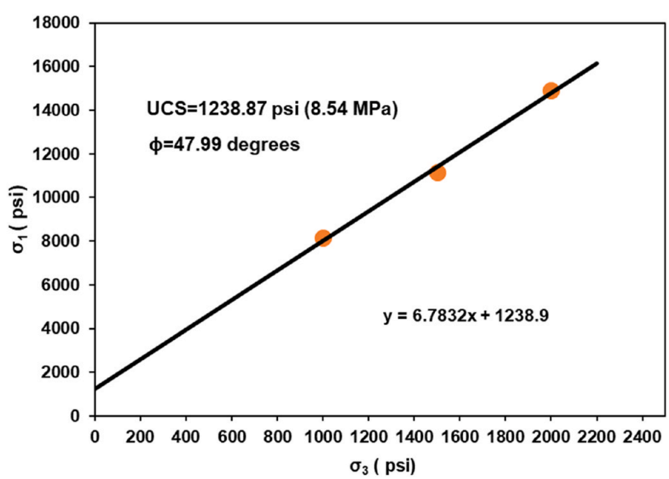

Fig. 12. Yield-based rock strength parameters (Zubair sandstone).

method for simplicity).

The following is the steps used to find the corrected *MCS*:

1. Record the value of *YS* at every stage of the MST
2. Get the difference between the MCS_{MST} (the point of sample's failure at the last stage of MST) and *YS* of the last stage of MST.
3. Use the following Equation (8) to find the corrected *MCS* for each stage (these values will be used to find rock strength parameters):

$$Corrected\_MCS = YS_{Any\_Stage} + \left(MCS_{MST} - YS_{Last\_Stage}\right) \quad (8)$$

where MCS_{MST} presents the failure point on the sample at the last stage of MST.

4. Use the corrected MCS values to estimate rock strength parameters

Fig. 13, Fig. 14, and Fig. 15 show rock strength parameters based on Equation (8) for Nahr Umr shale, Zubair shale, and Zubair sandstone, respectively.

3.3. MST & SST-based rock strength parameters

3.3.1. Case 3: corrected MCS based on MCS_{SST} & MCS_{MST}

This is another method that is tested in this paper. Rock strength parameters can be obtained based on one SST test and MST. In this case, the following equation is used to correct *MCS*:

$$Corrected\_MCS = YS_{Any\_Stage} + (MCS_{SST} - MCS_{MST}) \quad (9)$$

Fig. 16, Fig. 17, and Fig. 18 show rock strength parameters based on MST and one SST test for Nahr Umr shale, Zubair shale, and Zubair sandstone, respectively.

3.3.2. Case 4: corrected MCS based on MCS_{SST} & $YS_{Last\ stage}$

This is another method tested in this paper where *MCS* can be corrected based on MCS_{SST} and YS_{Last_Stage} (yield strength from the last stage of MST). In this case, the following equation is used to compute corrected MCS that can be used to estimate rock strength parameters:

$$Corrected\_MCS = YS_{Any\_Stage} + \left(MCS_{SST} - YS_{Last\_Stage}\right) \quad (10)$$

Fig. 19, Fig. 20, and Fig. 21 show rock strength parameters based on MCS_{SST} and YS_{Last_Stage} for Nahr Umr shale, Zubair shale, and Zubair sandstone, respectively.

3.4. Comparison with Based Case

In this subsection, the results of Cases 1–4 will be compared with the results of the Base Case (SST-based rock strength parameters). Table 2 shows the values of *UCS* and S_o based on all cases and for the three zones (Nahr Umr shale, Zubair shale, and Zubair sandstone) examined in this work. Although Case 1 is the most common method used to estimate

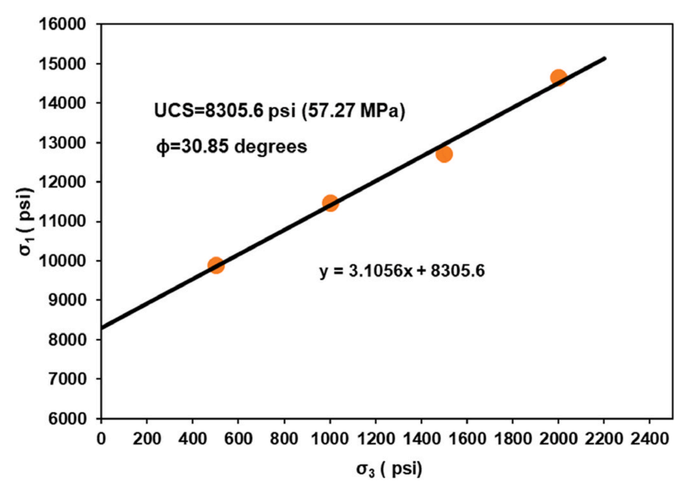

Fig. 13. Corrected MCS-Based rock strength parameters (Nahr Umr shale).

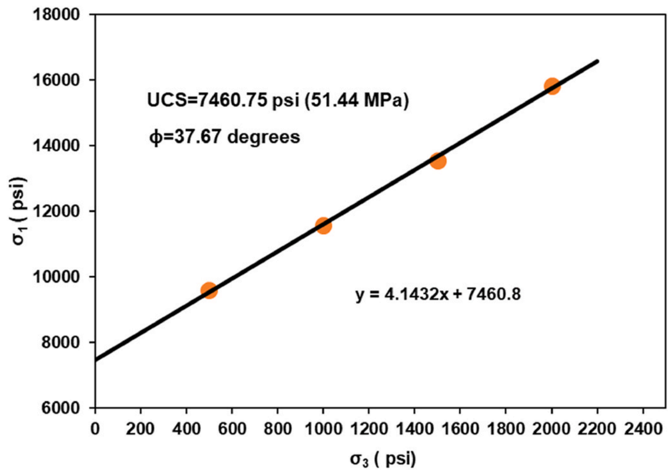

Fig. 14. Corrected MCS-Based rock strength parameters (Zubair shale).

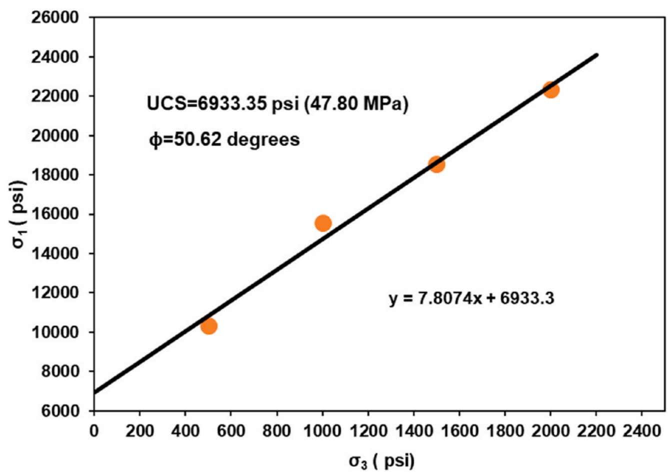

Fig. 15. Corrected MCS-Based rock strength parameters (Zubair sandstone).

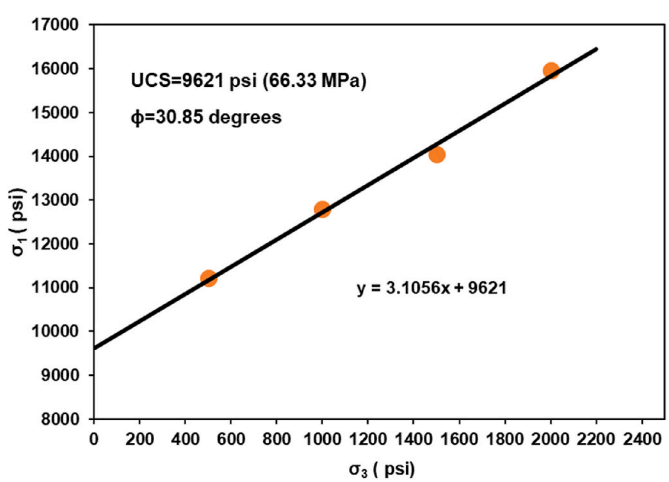

Fig. 16. Corrected MCS based on MCS_{SST} & MCS_{MST} rock strength parameters (Nahr Umr shale).

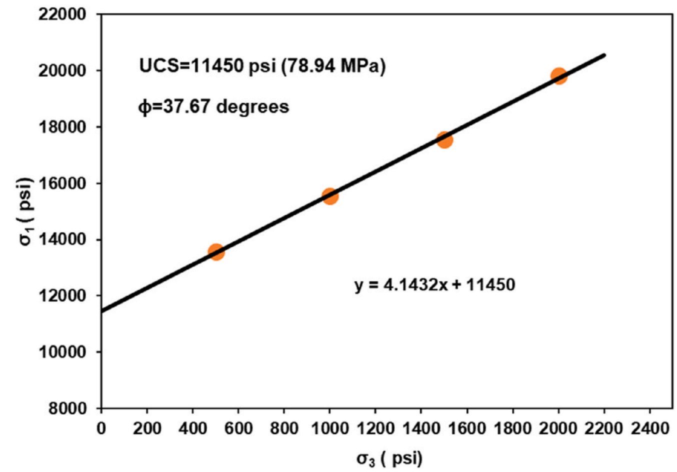

Fig. 17. Corrected *MCS* based on MCS_{SST} & MCS_{MST} rock strength parameters (Zubair shale).

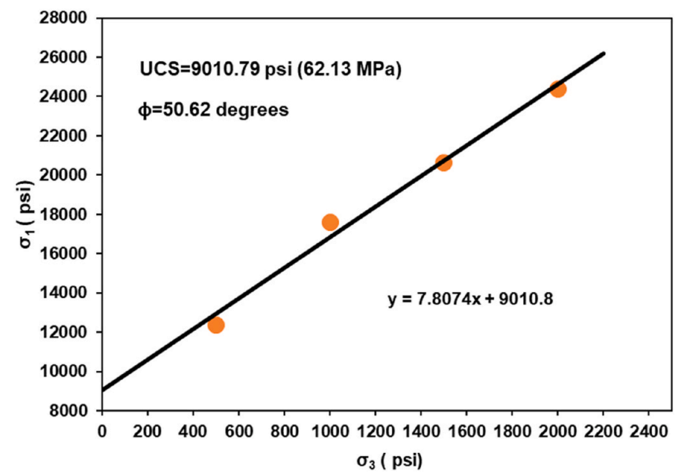

Fig. 18. Corrected MCS based on MCS_{SST} & MCS_{MST} rock strength parameters (Zubair sandstone).

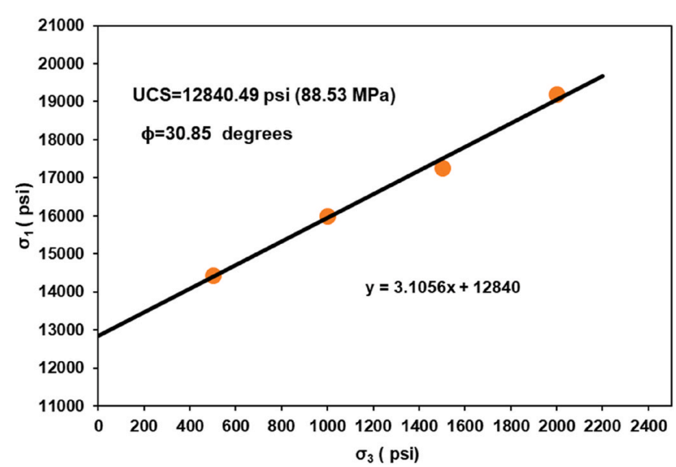

Fig. 19. Corrected MCS based on MCS_{SST} & $YS_{Last\ Stage}$ rock strength parameters (Nahr Umr shale).

rock strength parameters from MST as discussed earlier, Case 1 has produced an underestimate of *UCS* and S_o by 41%, 31%, and 83% for Nahr Umr shale, Zubair shale, and Zubair sandstone, respectively. This change is significant and may hinder creating robust geomechanical models. The A-HAS method (Case 2) is the new method proposed by this work that has produced an underestimate of *UCS* and S_o by only 4%, 3%, and 2% for Nahr Umr shale, Zubair shale, and Zubair sandstone,

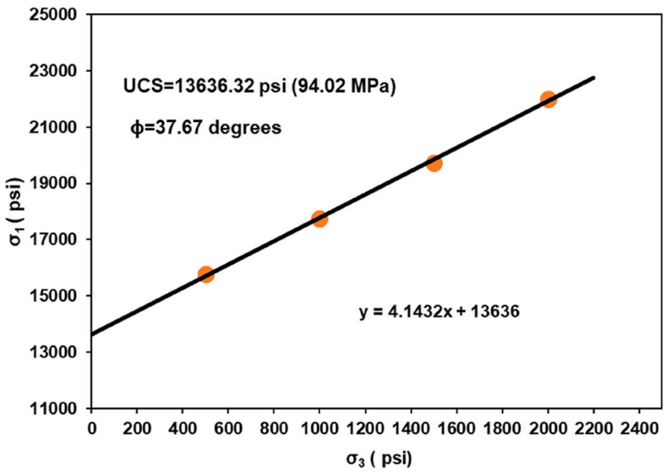

Fig. 20. Corrected *MCS* based on MCS_{SST} & $YS_{Last\ Stage}$ rock strength parameters (Zubair shale).

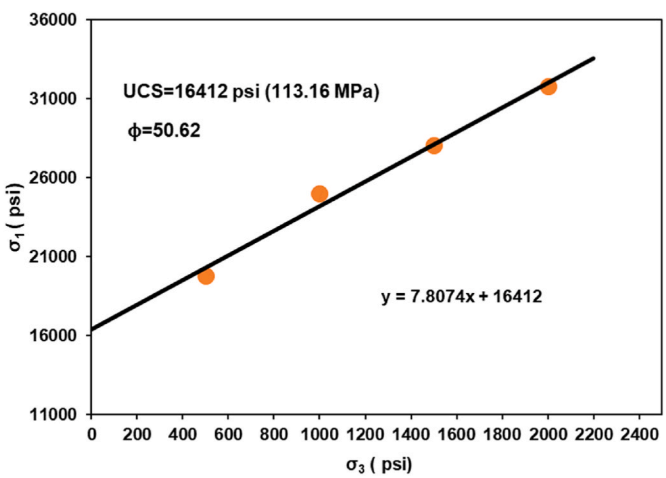

Fig. 21. Corrected MCS based on MCS_{SST} & $YS_{Last\ Stage}$ rock strength parameters (Zubair sandstone).

respectively. The A-HAS method provided the closest values of *UCS* and S_o to the Base Case among the other cases. Furthermore, Case 3 overestimated *UCS* and S_o by 11%, 49%, and 27% while Case 4 overestimated *UCS* and S_o by 48%,77%, and 131% for Nahr Umr shale, Zubair shale, and Zubair sandstone, respectively. There was no significant difference in the estimations of ϕ and μ_i among all cases when compared with the results of the Base Case as shown in Table 3. Therefore, the methods used to find rock strength parameters significantly affect *UCS* and S_o while they do not have a significant effect on ϕ and μ_i. Fig. 22 shows the % change in *UCS* and S_o between Base Case and Cases 1-4.

3.5. Implications of underestimating/overestimating UCS

As mentioned earlier regardless of the method used to estimate rock strength parameter (Base Case or Cases 1–4), only *UCS* and S_o will be affected while ϕ and μ_i will be less than 1% different (excluding Case 1 for the Zubair sandstone which had a 5.3% difference) from the Base Case. Furthermore, since S_o can be derived from *UCS* and μ_i (almost constant among all cases); thus, *UCS* is the only parameter that will be discussed further. In this subsection, the implication of overestimating/underestimating *UCS* will be discussed to provide further insights into the importance of accurately estimating *UCS* and the recommended method to get the best estimation of *UCS* from MST. Although yield-based *UCS* (Case 1) is the most common method used to estimate rock strength parameters from MST in the literature, it has significantly underestimated *UCS* between 31 and 83%. This underestimation is significant because it will hinder creating robust geomechanical models for wellbore stability, sand control, hydraulic fracturing, etc.

In wellbore stability, as an example, underestimating *UCS* will lead to underestimating rock strength. When designing a minimum mud weight to avoid collapse, the recommended mud weight to avoid collapse will be overly conservative (higher than needed to be). This may lead to a differential stuck pipe due to the hydrostatic static pressure of the selected mud weight being much higher than the formation pressure, particularly in front of permeable zones. This can lead to extra non-productive time (NPT), meaning extra cost. Furthermore, aiming for a higher than needed mud weight to avoid collapse requires more materials to be added to the drilling fluid to achieve this goal such as barite, CMC, etc.; which in turn leads to a higher cost of drilling fluid. On the other hand, in the case of overestimating *UCS*, meaning overestimating rock strength, can lead to designing mud weight window to avoid collapse to be smaller than actually needed. This, in return, will lead to having collapse issues and mechanical stuck pipes, as well as kick or blowout.

Another example is sand control. It is important to know if a well will produce sand or not prior to producing to plan a sand control method. One method to predict if a well will produce sand is using *UCS*. This method assumes that sand production will occur if the drawdown in the reservoir exceeds *UCS* (Abbas et al., 2018b; Bratli and Risnes, 1981). Therefore, underestimating or overestimating *UCS* can affect the well planning in terms of preparation for sand control. Moreover, *UCS* can have a role in the formation of complex hydraulic fractures (Nagaso et al., 2019).

Table 2
Summary of UCS & S_o results of all cases.

Zone	Case	UCS (psi)	UCS % Change from Base Case	S_o (psi)	S_o % Change from Base Case
Nahr Umr	Base Case	8665		2455	
	Case 1	5086	−41%	1443	−41%
	Case 2 (A-HAS Method)	8306	−4%	2356	−4%
	Case 3	9621	11%	2730	11%
	Case 4	12,840	48%	3643	48%
Zubair Shale	Base Case	7691		1888	
	Case 1	5274	−31%	1296	−31%
	Case 2 (A-HAS Method)	7461	−3%	1833	−3%
	Case 3	11,450	49%	2813	49%
	Case 4	13,636	77%	3350	77%
Zubair Sandstone	Base Case	7097		1268	
	Case 1	1239	−83%	238	−81%
	Case 2 (A-HAS Method)	6933	−2%	1241	−2%
	Case 3	9011	27%	1612	27%
	Case 4	16,412	131%	2937	132%

Table 3
Summary of ϕ & μ_i results of all cases.

Zone	Case	ϕ (Degrees)	ϕ % Change from Base Case	μ_i	μ_i % Change from Base Case
Nahr Umr	Base Case	30.930		0.5992	
	Case 1	30.855	−0.244%	0.5974	−0.298%
	Case 2 (A-HAS Method)	30.855	−0.243%	0.5974	−0.297%
	Case 3	30.855	−0.243%	0.5974	−0.297%
	Case 4	30.855	−0.243%	0.5974	−0.297%
Zubair Shale	Base Case	37.700		0.7729	
	Case 1	37.672	−0.075%	0.7721	−0.102%
	Case 2 (A-HAS Method)	37.672	−0.075%	0.7721	−0.102%
	Case 3	37.672	−0.075%	0.7721	−0.102%
	Case 4	37.672	−0.075%	0.7721	−0.102%
Zubair Sandstone	Base Case	50.670		1.2205	
	Case 1	47.991	5.288%	1.1103	−9.030%
	Case 2 (A-HAS Method)	50.617	0.105%	1.2181	−0.190%
	Case 3	50.617	0.105%	1.2181	−0.190%
	Case 4	50.617	0.105%	1.2181	−0.190%

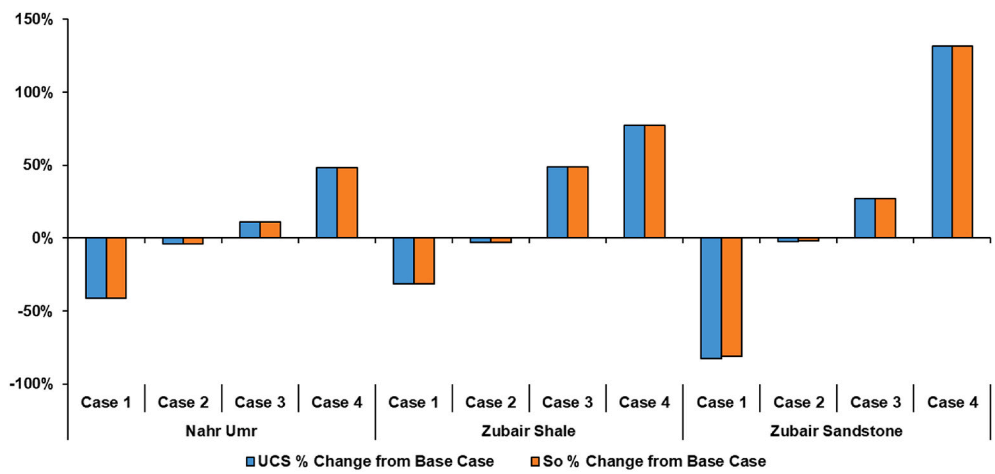

Fig. 22. UCS and S_o comparison between base case and cases 1-4.

In short, the currently used method to estimate rock strength parameters from MST based on yield strength (Case 1) has fallen short in the estimation of *UCS*. Case 1 underestimated rock *UCS* by as high as 83% which is very significant and can hinder creating a robust geomechanical model for different applications. On the other hand, the A-HAS method (Case 2) proposed by the authors which is correcting the yield strength based on the last stage of MST (Equation (8)) has provided much better results of the actual *UCS* with the highest error being 4% that is minor and can be ignored. The A-HAS method was tested on three diverse zones (Nahr Umr shale, Zubair shale, and Zubair sandstone) and has significantly outperformed the currently used yield-based rock strength parameters (Case 1). The authors strongly recommend utilizing the A-HAS method to estimate rock strength parameters from MST over any other methods (especially the currently used yield-based method) due to its effectiveness and precision at estimating rock strength parameters (especially *UCS* and S_o). This method can provide a precise estimation for rock strength parameters from MST instead of SST to save time, money, and material.

4. Conclusions

After conducting SST and MST tests on core plugs from three zones (Nahr Umr shale, Zubair shale, and Zubair sandstone) and testing four methods (Cases 1–4) to find the best way to estimate rock strength parameters from MST tests, the following conclusions were made:

- Regardless of the method used to estimate rock strength parameters, ϕ and μ_i were not significantly affected by the method and the errors between the Base Case (SST case) and all other methods were not significant.
- The paraments that were significantly affected by the method used to estimate rock strength parameters were *UCS* and S_o.
- Comparing *UCS* and S_o results of the yield-based method (Case 1) and the A-HAS method (Case 2) to the Base Case, the A-HAS method has remarkably outperformed the yield-based method in all three zones tested.
- The proposed A-HAS method has provided an error of 4%, 3%, and 2% for Nahr Umr shale, Zubair shale, and Zubair sandstone, respectively while the yield-based method resulted in errors of 41%, 31%, 83% for Nahr Umr shale, Zubair shale, and Zubair sandstone, respectively. The error in the estimation of *UCS* and S_o from the currently used yield-based method is very significant and can impede building robust geomechanical models for wellbore stability, sand production, and hydraulic fracturing.
- The novel A-HAS method (Case 2) proposed by this research is recommended to be utilized to estimate rock strength parameters from MST due to its accuracy over the currently used yield-based (Case 1), where the A-HAS method has remarkably outperformed the yield-based method.
- By using the A-HAS method, rock strength parameters can be estimated from MST tests within a negligible margin of error (highest 4% error in *UCS* and S_o based the tested zones) without the need of conducting SST tests which will save time, money, and material.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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