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Comparison and Verification of Two Models which Predict Minimum Principal In Situ Stress from Triaxial Data

ABSTRACT

This paper evaluates the correlation between values of minimum principal *in situ* stress derived from two different models which use data obtained from triaxial core tests and coefficient for earth at rest correlations. Both models use triaxial laboratory tests with different confining pressures. The first method uses a verified fit to the Mohr failure envelope as a function of average rock grain size, which was obtained from detailed microscopic analyses. The second method uses the Mohr-Coulomb failure criterion. Both approaches give an angle of internal friction which is used to calculate the coefficient for earth at rest which gives the minimum principal *in situ* stress. The minimum principal *in situ* stress is then compared to actual field mini-frac test data which accurately determine the minimum principal *in situ* stress and are used to verify the accuracy of the correlations. The cores and the mini-frac stress test were obtained from two wells, the Gas Research Institute's (GRI's) Staged Field Experiment (SFE) #1 well through the Travis Peak Formation in the East Texas Basin, and the Department of Energy's (DOE's) Multiwell Experiment (MWX) wells located west-southwest of the town of Rifle, Colorado, near the Rulison gas field. Results from this study indicate that the calculated minimum principal *in situ* stress values obtained by utilizing the rock failure envelope as a function of average rock grain size correlation are in better agreement with the measured stress values (from mini-frac tests) than those obtained utilizing the Mohr-Coulomb failure criterion.

INTRODUCTION

There are many available techniques for measuring *in situ* stress at depth in a wellbore, but all of the methods suffer disadvantages. Core-based methods, including anelastic strain recovery, differential strain curve analysis, shear acoustic anisotropy, acoustic emissions and others, all require the taking of core and detailed analysis. Furthermore, problems with core quality, rock fabric, and other factors may degrade the accuracy of the stress estimate. Direct measurements using small volume hydraulic fractures have fewer analysis problems, but they are expensive and may not be compatible with the well completion scheme, particularly if measurements will be made in layers above the pay zone.

The ideal situation would be to measure stress directly from logs or drilling data. Attempts to use sonic logs have yielded poor results, primarily because of the questionable assumption of elastic, uniaxial-strain behavior and an uncertain poro-elastic parameter. However, this particular failure does not necessarily mean that other techniques cannot or will not be developed. One alternate hypothesis is to assume that all rocks are in an incipient failure state[1] and to calculate the minimum stress that would be obtained for any overburden stress at such a condition. Such a hypothesis could be applied to either log, core or drilling data. The

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primary difficulty is relating the failure criterion to some measurable log, core or drilling properties. This work investigates the accuracy of predicting minimum principal *in situ* stress magnitude from two failure models and compares the results to the minimum principal *in situ* stress from mini-frac tests.

TECHNICAL DISCUSSION

Laboratory triaxial test data are used by both models to predict the minimum principal in situ stress. The angle of internal friction is calculated from these two approaches. The coefficient of earth at rest and, thus, the minimum principal *in situ* stress, are obtained from the angle of internal friction.

Normalized Rock Failure Envelope Model as a Function of Average Rock Grain Size

The Normalized Rock Failure Envelope method utilizes a normalized form of Mohr failure envelope[2] which can be obtained from the following normalized equation fit to different lithologies:

$$\sigma = \sigma_o + a(1 - e^{-bP}) \quad (1)$$

where

- σ = confined compressive strength, psi
- σ_o = unconfined compressive strength, psi
- P = confining pressure, psi
- a, b = empirically determined constants

The normalized correlation was obtained in an earlier work[2] on SFE #1. In this work the coefficient 'a' was obtained as a function of mean grain size:

$$a = 10^{(1.948 + 4.009 * \mu)} \quad (2)$$

where

μ = mean rock grain size, mm

Coefficient 'b' was obtained as a function of coefficient 'a' from the following equation:

$$b = 10^{(1.982 - 1.4 * \log a)} \quad (3)$$

The rock compressive strength σ from equation (1) has earlier been shown to match the rock triaxial compressive strength.

Minimum Principal *In Situ* Stress, Angle of Internal Friction and Coefficient for Earth at Rest

The unconfined rock compressive strength values were obtained from triaxial tests reported for the SFE[3] and MWX[4] wells. The minimum principal *in situ* stress using Mohr failure-envelope theory is given by the following equation:

$$\sigma_h = K_o(\sigma_{ob} - P_p) + P_p \quad (4)$$

where

- σ_h = minimum principal *in situ* stress, psi
- σ_{ob} = overburden stress, psi
- P_p = pore pressure, psi
- K_o = coefficient of earth at rest, dimensionless

For the two data sets studied at every stress test depth interval, the value of pore pressure and overburden stress is available from published data[3-6]. The process of finding the correct value of K_o is shown below. Relationships for K_o determined for rock at failure, were obtained experimentally by different investigators[7-9] as follows:

For sandstone

$$K_o = 1 - Sin\beta \quad (5)$$

and for shale

$$K_o = 0.9(1 - Sin\beta) \quad (6)$$

where

β = the angle of internal friction at failure, degrees

Equation (6) for the minimum principal *in situ* stress requires the value of K_o which is based on β. The equation for obtaining the angle of internal friction, β, is given by

$$\beta = \arcsin\left(\frac{\sigma_2 - \sigma_1}{\sigma_2 - \sigma_1 + 4\Delta}\right) \quad (7)$$

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where

$$\sigma_1 = \sigma_o + (1 - e^{-bP_{e-\Delta}}) \quad \text{...(8)}$$

$$\sigma_2 = \sigma_o + (1 - e^{-bP_{e+\Delta}}) \quad \text{...(9)}$$

and

Δ = arbitrary small value of pressure, psi

$P_{e+\Delta}, P_{e-\Delta}$ = *In situ* confining pressures at small values Δ about a nominal confining pressure, psi

Mohr-Coulomb Failure Model:

To obtain the value of the coefficient for earth at rest, K_o the Mohr-Coulomb failure model uses the same equations as the normalized rock failure envelope as a function of average rock grain size correlation. This method uses the average value of angle of internal friction obtained for different triaxial tests. The equation for β is the same one used for the normalized rock failure envelope approach except that the values of σ are those obtained from triaxial tests. The average value of β obtained using different compressive strengths is used in the equations (5) or (6) (depending on lithology) to obtain K_o which is then used in equation (4) to obtain the minimum principal *in situ* stress.

In all the minimum principal *in situ* stress calculations, the poroelastic parameter (commonly denoted α) multiplying the pore pressure is assumed to be unity, which is in good agreement with lab measured values[10].

Steps Required to Obtain Minimum Principal *In Situ* Stress

The minimum principal *in situ* stress is obtained from equation (4) utilizing the following procedure:

Step 1:

An initial guess for σ_h is assumed.

Step 2:

The values of $P_{e+\Delta}$, $P_{e-\Delta}$ are calculated as the difference between the value of the initial guess for σ_h and the pore pressure, P_p

$$P_{e\pm\Delta} = \sigma_h - P_p \quad \text{...(10)}$$

Step 3:

The value of the coefficients a and b are determined from equations (2) and (3). Angle of internal friction, β is then calculated from equation (7).

Step 4:

The value of β from step 3 is used in equations (5) or (6) (depending on lithology) and a value of K_o is calculated. This value of K_o is then used in equation (4) to calculate σ_h.

Step 5:

The value of σ_h obtained from step 4 is then compared to the initial guess. The calculated value is then input as the guess for the next iteration. The process is repeated until successive values of σ_h converge.

RESULTS AND DISCUSSION

Staged Field Experiment No.1

A listing of measured and computed minimum principal *in situ* stresses for SFE #1 is given in Table 2. The measured stress values for the depth intervals are taken from published data[3]. Figures 1 and 2 show a comparison of measured and calculated stress values for SFE #1. The calculated values using normalized rock failure envelope approach for sandstone match the stress tests (Figure 1). For the shales, two of three data points agree reasonably with the measured values. This is believed to be because pore pressure in shales is very difficult to measure and must be assumed. The calculated values for minimum principal *in situ* stress using the Mohr-Coulomb failure criterion are not as accurate in the sandstones as the normalized rock failure envelope as a function of average rock grain size approach. The shale values are also off for the Mohr-Coulomb approach as in the case of Normalized Rock failure Envelope as a function of average rock grain size approach.

Multi Well Experiment

Stress calculations based on data obtained from the Multiwell Experiment wells[11,12] do not provide any insight in choosing the best method. Table 2 gives a listing of measured and computed *in situ* stresses for the MWX wells. Figures 3 and 4 show a comparison of the stress values obtained from mini-frac tests as well as calculation using Normalized rock failure approach and Mohr-Coulomb approach. Both approaches under-predict the minimum principal in situ stress values for sandstones. For the shale data, both approaches are off.

DISCUSSION

Results for the MWX wells indicate that the calculated stress values are much less than the measured stress values. Although the reasons for the under-prediction of calculated stress values are not known accurately, the probable causes could be the following:

1. One main reason for the uncertainty in stress values is due to to the uncertainty in measured pore pressure values. This is especially true for shaly formations.

2. The stress test data is from laboratory measurements performed on cores. For the measurements to be meaningful, considerable care and effort should be expended to insure that the *in situ* wettability is preserved during coring, surfacing, storage, and measurement operations. Failure to preserve native wettability will cause the measured values of stress to be of little use for analysis.

3. In both approaches the poroelastic constant, α, is assumed to be 1. This is not always the case and a reduction in α will actually worsen our predictions. But in conjunction with points 1, 2, 4 and 5 in the discussion the two results might be reasonable.

4. Laboratory triaxial test data are obtained under much higher strain rates than those that would be found under natural compaction of rocks. Therefore, the laboratory values of stress would be much higher than the actual values. This might be the reason for the large difference in measured and calculated stress values for MWX wells.

5. The MWX wells are located in the valley of the Colorado river. This factor is not accounted for while measuring the overburden stress. Clark[13] has shown that the topography of the MWX wells could increase the stress values by an average of 500 - 1500 psi. Figures 5 and 6 show the modified stress values which have been increased by an average 800 psi. As can be seen, the values of sandstones are now in agreement with the measured values. Both approaches seem to give approximately the same answer.

CONCLUSIONS

Based on this study the following conclusions can be drawn:

1. The process of calculating the Minimum Principal *In Situ* Stress is more suitable for sandstone lithology than for shale. This is believed to be due to the uncertainty in the pore pressure values obtained for shale.

2. An analysis of the results for the MWX wells indicate that the addition of a constant term in the stress equation to account for the topography brings the calculated values close to the measured values. An earlier work[13] on this aspect found that the addition of 800 psi to the stress values to account for topographical effects would bring the calculated stress values close to the measured values. Thus, equation (2) can be modified to include a constant term, T as

$$\sigma_h = K_o(\sigma_{ob} - P_p) + P_p + T \cdots\cdots\cdots\cdots (9)$$

From an analysis of the calculated values of *in situ* stresses for shales, it was found that the value of T would vary from 500 to 1500 psi to match the stress test data. As shown in figures 5 and 6 an ideal value for T would be 800 psi.

3. Of the two approaches used in obtaining the minimum principal *in situ* stress, the normalized rock failure envelope as a function of average rock grain size approach gives better results than those obtained by using the Mohr-Coulomb approach.

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Table 1. Listing of Measured and Computed *In Situ* Stresses for SFE #1

Test depth, ft	Lithology	Unconfined rock strength,psi	Angle of internal friction,deg Normalized Rock Failure envelope	Angle of internal friction,deg Mohr Coulomb failure criterion	Measured Minimum Principal Insitu Stress, psi	Calculated Insitu Stress,psi Normalized Rock Failure Envelope	Calculated Insitu Stress,psi Mohr-Coulomb Failure Criterion
6163-6165	Shale	5,450	52.9	48.8	3415	3756	3906
6193-6195	Sandstone	18,662	54.1	50.2	3029	3800	3956
6243-6245	Sandstone	37,300	52.1	52.5	3497	3912	3893
7209-7211	Shale	7,100	52.2	55.3	4146	4418	4296
7465-7467	Sandstone	24,600	52.8	57.6	3860	4640	4430
7487-7489	Shale	9,300	51.6	46.2	5346	4619	4869

Table 1. Listing of Measured and Computed *In Situ* Stresses for MWX Wells

Test depth,ft	Lithology	Unconfined rock strength,psi	Angle of internal friction,deg Normalized Rock Failure Envelope	Angle of internal friction,deg Mohr-Coulomb Failure Criterion	Measured Minimum Principal Insitu Stress, psi	Calculated Insitu Stress,psi Normalized Rock FailureEnvelope	Calculated Insitu Stress,psi Mohr-Coulomb Failure Criterion
5044-5046	Sandstone	13,489	42.7	38.8	4460	3703	3572
5700-5702	Mudstone	24,466	52	56.2	5149	3615	3723
5721-5723	Sandstone	11,728	48.3	53.3	4575	3748	3905
5757-5759	Mudstone	14,165	43.8	55.9	5439	3632	3980
5940-5942	Mudstone	15,008	48.7	54.7	5750	3936	4096
5962-5964	Sandstone	15,211	48.6	52	4600	4070	4174
6442-6444	Sandstone	15,182	46.2	54.8	5720	4793	5022
6460-6462	Sandstone	12,137	42.2	55.1	5670	4787	5149
6512-6514	Sandstone	14,138	41.9	55.7	5845	4782	5175
6565-6567	Mudstone	15,211	55	56.7	6980	4725	4763
7263-7265	Sandstone	10,220	35.3	53.2	6755	5952	6402

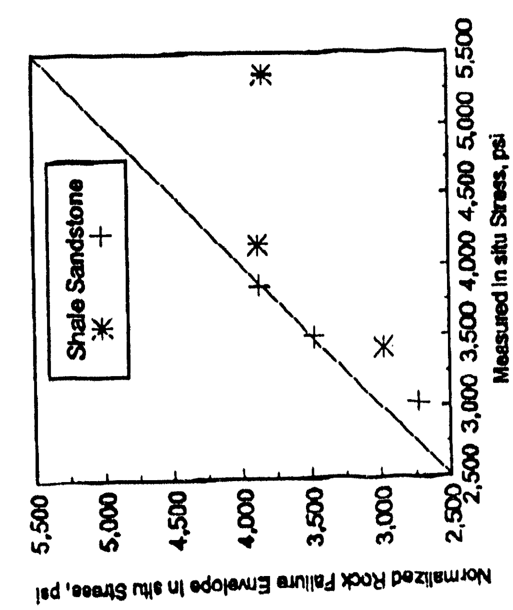

Figure 1. Comparison of stresses for SFE #1 well

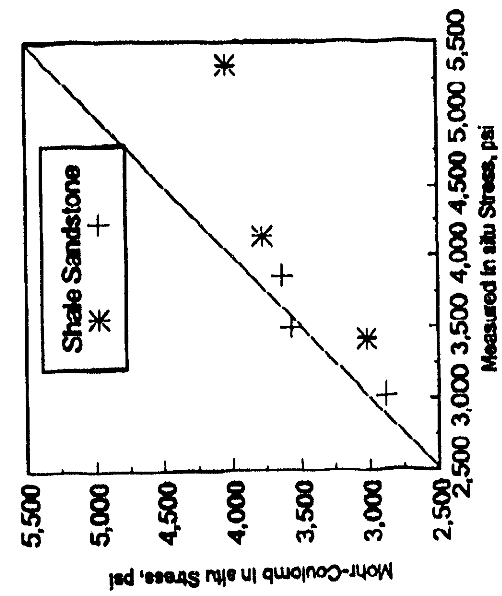

Figure 2. Comparison of stresses for SFE #1 well

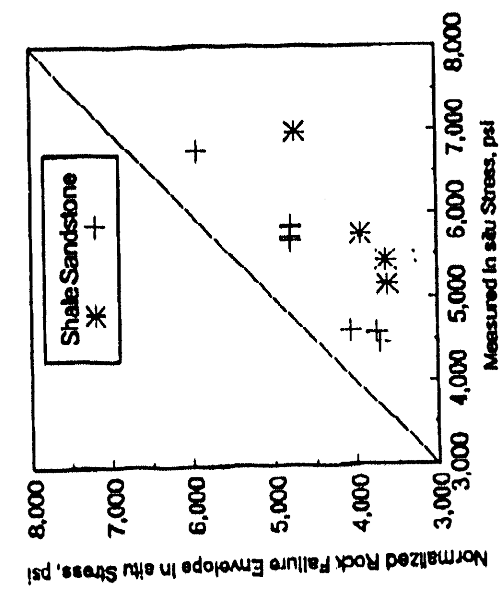

Figure 3. Comparison of stresses for MWX wells

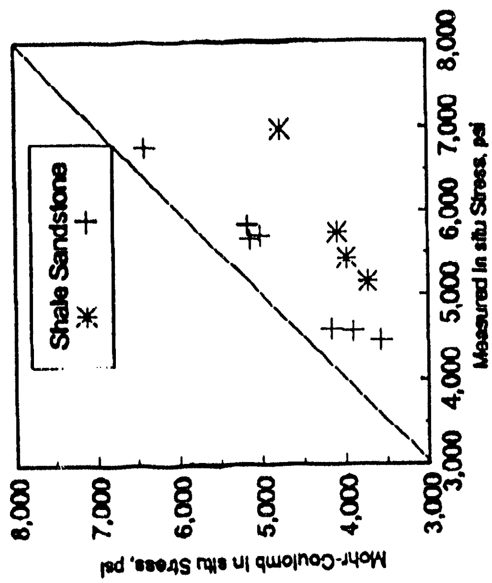

Figure 4. Comparison of stresses for MWX wells

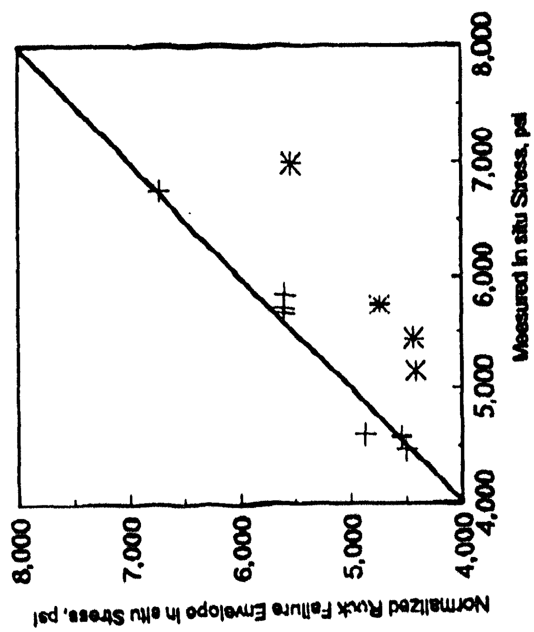

Figure 5. Comparison of stresses for MWX wells

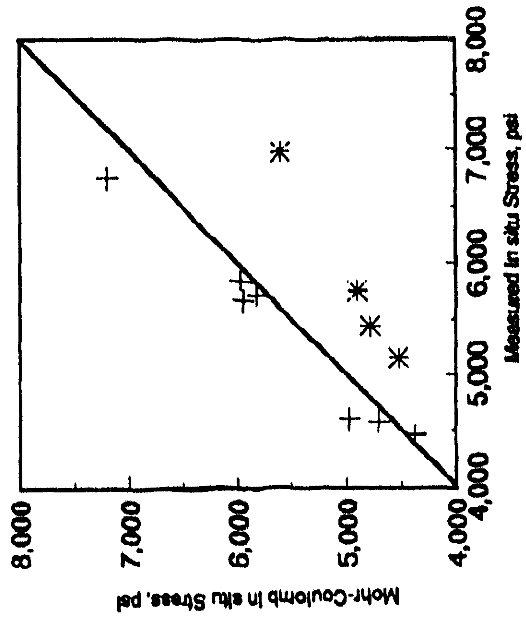

Figure 6. Comparison of stresses for MWX wells

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