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EFFECT OF MUD FILTER CAKE EFFICIENCY ON WELLBORE STABILITY DURING DRILLING OPERATIONS

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ABSTRACT

Drilling is the only way for direct contact with the hydrocarbon reservoir. Wellbore stability during drilling is necessary and any miscalculations may result in a complete loss of the drilled hole. The stability of the drilled hole is function of rock strength and pore pressure penetration (build-up). Pore pressure build-up was found to be directly proportional to the mud cake efficiency. Therefore, any attempt to model the wellbore stability must take into account the effect of mud cake efficiency. In this study a model accounting for pore pressure, in-situ stresses, rock strength properties and mud cake efficiency has been developed to study the stability of vertical wells (parallel to s_{zz}).

1. INTRODUCTION

The importance of the study of wellbore stability is that in occasion of wellbore instability, lost circulation (tensile failure) or spalling and/or tight hole (compression failure) may occur which can result in stuck pipe and / or loss of the drilled wellbore [1-7]. Before a well is drilled, compression stresses exist within the rock formation. The stresses can be resolved into a vertical or overburden stress (σ_{zz}) and two horizontal stresses, the maximum(σ_H) and the minimum (σ_h) horizontal stresses. In order to stabilize the drilled formations, the well is filled with a drilling mud which replaces the initial support given by the drilled out rocks; therefore, the original (in-situ) rock stresses in the vicinity of the wellbore are redistributed (see Fig.1) by the

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hydraulic pressure of the mud (σ_r), the tangential stress (σ_θ) and the axial stress(σ_z) as well as a shear stress in deviated wellbore ($\tau_{\theta z}$). If one of the redistributed stresses exceeds the rock strength, then instability occurs.

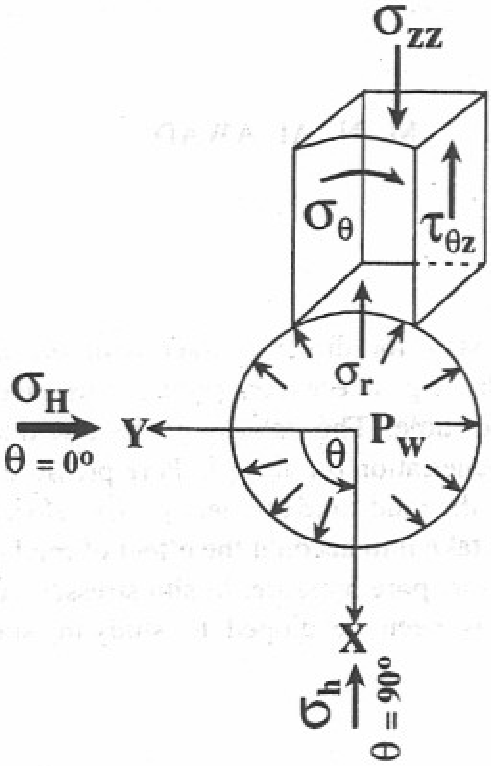


Fig. 1. Redistributed stress state around wellbore.

The drilling mud deposits a filter cake which controls the pore pressure build-up caused by mud filtrate invasion into the drilled formations. If low quality mud cake (i.e. highly permeable) is formed on the wellbore walls, then the formation pore pressure begins to approach the wellbore pressure. The equilibrium between the pore pressure and the wellbore pressure will minimize the stability effect of the mud cake. Therefore, the quality of the mud cake must be thoroughly checked for any type of mud before it is used in the field operations.

2. OBJECTIVES

Many researchers have studied the problem of wellbore stability [1-7]. Most of these studies neglected the effect of mud cake efficiency. In a recent study, mud cake efficiency was measured at laboratory using core plugs [8]. This was done to investigate the reasons beyond some wellbore instabilities occurred during drilling operations. In there measurements, preserved core plugs were contaminated with drilling fluids identical to those used when the instabilities occurred. Therefore the effect of mud cake efficiency on wellbore stability must be considered if accurate modelling is to be developed. In this paper, a mathematical model has been developed by the integration of mud cake efficiency and the Mohr-Coulomb failure criteria into the poro-elastic stress solution. The developed model can be used to study the stability of vertical, inclined and horizontal wells during drilling operations.

3. THE MATHEMATICAL MODEL

For homogeneous, isotropic and linear poro-elastic materials, Kirsch solution for poro-elastic materials is used to model the redistributed stresses around the wellbore:

$$\begin{aligned}
&\sigma_r = P_w \\
&\sigma_\theta = \left(\sigma_x + \sigma_y - P_w\right) - 2\left(\sigma_x - \sigma_y\right)\mathrm{Cos}2\theta - 4\tau_{xy}\mathrm{Sin}2\theta \\
&\sigma_z = \sigma_{zz} - 2\nu\left(\sigma_x - \sigma_y\right)\mathrm{Cos}2\theta - 4\nu\tau_{xy}\mathrm{Sin}2\theta \\
&\tau_{r\theta} = \tau_{rz} = 0 \\
&\tau_{\theta z} = 2\left[-\tau_{zx}\mathrm{Sin}\theta + \tau_{yz}\mathrm{Cos}\theta\right]
\end{aligned} \qquad (1)$$

$$
\begin{aligned}
\sigma_1 &= \sigma_r = P_w \\
\sigma_2 &= \frac{1}{2}\left(\sigma_\theta + \sigma_z\right) - \frac{1}{2}\sqrt{\left(\sigma_\theta - \sigma_z\right)^2 + 4\tau_{\theta z}} \qquad (2) \\
\sigma_3 &= \frac{1}{2}\left(\sigma_\theta + \sigma_z\right) + \frac{1}{2}\sqrt{\left(\sigma_\theta - \sigma_z\right)^2 + 4\tau_{\theta z}}
\end{aligned}
$$

Pore pressure penetration (build-up) is incorporated into the Kirsch solution by the application of the principle of effective stresses as follows:

$$\bar{\sigma} = \sigma - P_p \qquad (3)$$

3.1 Rock Failure Criteria

Three obvious mechanisms causing borehole failure are shear, compressive and tensile failures. One of the most used failure theories is the Mohr-Coulomb failure criterion. This criterion is defined as follows:

$$\tau_f = \tau_o + \sigma \tan\phi \qquad (4)$$

$$\sigma_c = \sigma_1 - k\sigma_3 \qquad (5)$$

When a rock is loaded beyond its elastic limit it will fail and its failure criteria can be established based on a series of triaxial compression tests on cylindrical rock specimens as shown in Fig. 2a. The effect of pore pressure build-up on rock stability can be clearly seen in Fig. 2b. Table 1 presents the mechanical and in-situ data used to investigate the effect of mud cake efficiency on wellbore stability.

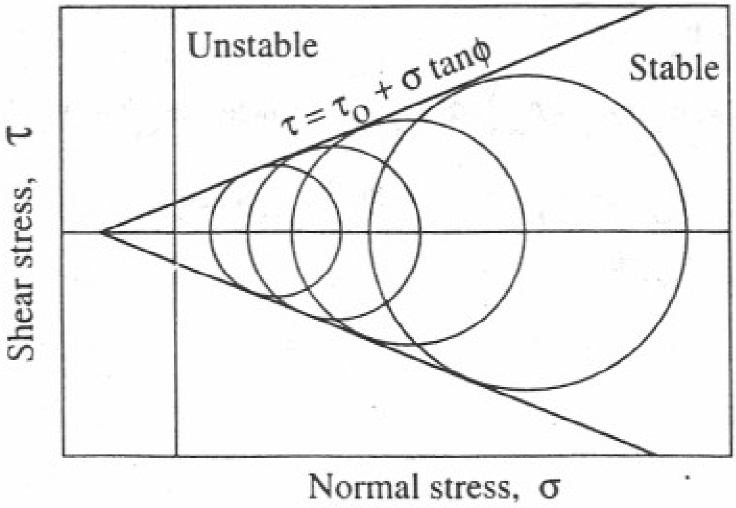


Fig. 2a. Construction technique of Mohr-Coulomb Failure envelope.

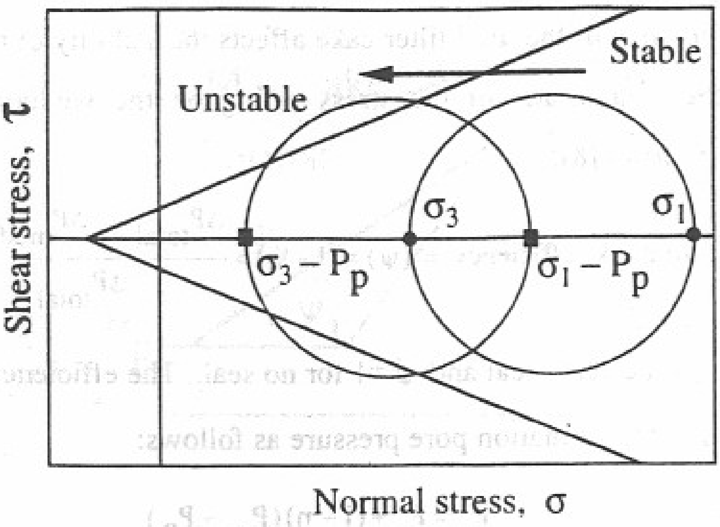


Fig. 2b. Effect of pore pressure build-up on rock failure criteria.

Table 1. Input data used in the study.

θ = 0 degree.
P_w = 83.3 psi/100ft.
P_p = 44.0 psi/100ft.
ϕ = 31 degree.
η = Varies from 0 to 1.
ν = 0.21
k = 3.1
Well depth = 9000 ft.
τ_o = 29.2 psi/100ft.
σ_h = 75.0 psi/100ft.
σ_H = 85.0 psi/100ft
σ_z = 100.0 psi/100ft.

3.2 Mud Cake Efficiency

The efficiency of the mud filter cake affects the stability of the wellbore because it controls the magnitude of the stress acting on the wellbore wall and can be formulated as follows [8].

$$\text{Mud cake efficiency} = (\psi) = (1-\eta) = \frac{\Delta P_{\text{total}} - \Delta P_{\text{mud cake}}}{\Delta P_{\text{total}}} \tag{6}$$

Where $\psi = 0$ for perfect seal and $\psi = 1$ for no seal. The efficiency of the mud cake is directly related to the formation pore pressure as follows:

$$P_p = P_p + (1-\eta)(P_w - P_P) \tag{7}$$

For high mud cake efficiency (Fig. 3a) the pressure drop from wellbore pressure to pore pressure occurs in the filter cake, therefore the formation remains undisturbed and sustains its initial strength. Whereas, for low mud cake efficiency (Fig. 3b) the pressure drop occurs inside the formation resulting in a build-up in the pore pressure and hence a reduction in formation strength which may lead to wellbore instability.

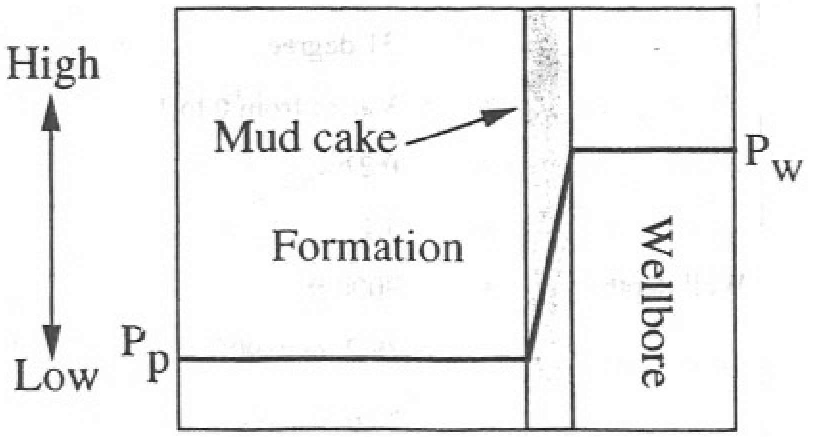
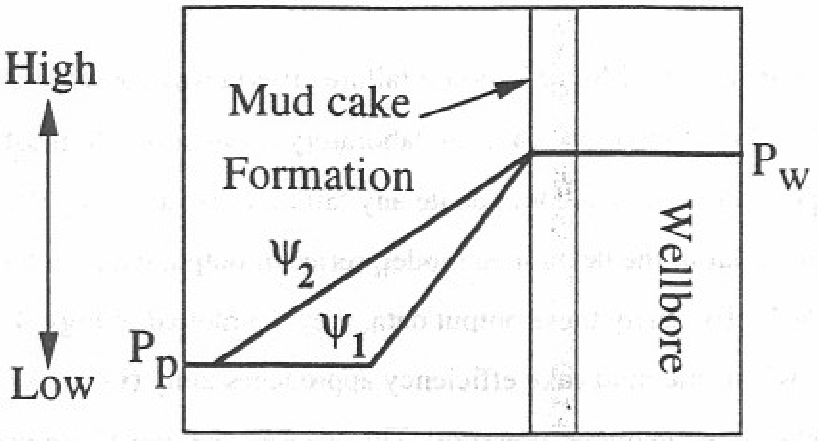


Fig. 3a. Pore pressure distribution for high efficiency mud cake.



Note: ψ_1 and ψ_2 are efficiences for two different drilling fluids and $\psi_2 > \psi_1$.

Fig. 3b. Pore pressure distribution for low efficiency mud cake.

Applying equations 1 to 7, the maximum and the minimum stresses acting on the wellbore wall can be calculated, whereas the altered values of the formation uniaxial compressive strength and the formation shear strength can be computed as follows:

$$\begin{aligned}\sigma_{1n} &= \mathrm{Max}\left[\bar{\sigma}_1, \bar{\sigma}_2, \bar{\sigma}_3\right] \\ \sigma_{3n} &= \mathrm{Min}\left[\bar{\sigma}_1, \bar{\sigma}_2, \bar{\sigma}_3\right]\end{aligned} \tag{8}$$

$$\sigma_c = \sigma_{1n} - k\sigma_{3n} \tag{9}$$

$$\tau_f = \tau_o + \left[\frac{\sigma_{1n} + \sigma_{3n}}{2}\right] \tan\phi \tag{10}$$

Therefore the stability of a wellbore can be predicted by the comparison between the initial and the altered values of the shear strength or the uniaxial compressive strength.

4. RESULTS AND DISCUSSION

In this study, Mohr-Coulomb failure criteria was considered due to its simplicity in application and to its ease in laboratory evaluation. It must be noticed that the developed model can accommodate any failure criteria. Using data presented in Table 1 as an input in the developed model, series of output data are obtained and tabulated in Table 2. To clarify these output data, they are plotted in Figs. 4 and 5. As seen from Fig. 4, when the mud cake efficiency approaches unity (i.e. no seal) the pore pressure approaches the wellbore pressure. This causes the radial support provided by the wellbore pressure to diminish and as a consequence, tensile forces will start to act on the borehole wall leading to formation fragmentation and caving of the already failed rock due to high compressive stresses as shown in Fig. 4 Fig. 5 represents the effect of mud cake efficiency magnitude on formation shear strength required to maintain wellbore stability. When the mud cake efficiency equal to zero, i.e. approaching perfect seal, the initial (natural) shear strength of the formation is quite enough to maintain wellbore stability. As the mud cake efficiency approaches unity, the shear strength required to maintain stability is greater than the natural shear strength, therefore, the formation will fail in shear. On other wards, failure will occur if the difference between the natural and the altered shear strengths are negative otherwise, the wellbore will be stable. It must be noticed that each drilling fluid has its own mud cake efficiency which changes with time during drilling. Thus, the drilling fluid needs continuos observation and treatment. Mud cake properties such as permeability and resistance to erosion highly control its efficiency. The efficiency of mud cake can be improved by the addition of filtration control and bridging agents and by avoiding turbulent flow in the open hole section of the well. Finally, it should be noticed that, the correct knowledge of the in-situ stress state and pore pressure and the perfect measurement of failure criteria are essential for correct wellbore stability predictions.

Table 2. Data calculated using the developed model.

Initial uniaxial compressive strength gradient = 58.3 psi/100ft				Initial shear strength gradient = 29.2 psi/100ft	
ψ	σ_1, psi/100ft	σ_2, psi/100ft	σ_3, psi/100ft	Altered uniaxial compressive strength gradient, psi/100ft	Altered shear strength gradient, psi/100ft
0.0	58.3	58.3	00.00	58.3	20.2
0.1	62.3	62.3	03.93	50.0	22.6
0.2	66.2	66.2	07.87	41.7	24.9
0.3	70.1	70.1	11.80	33.3	27.3
0.4	74.1	74.1	15.70	23.9	29.7
0.5	78.0	78.0	19.70	15.0	32.0
0.6	81.9	81.9	23.60	06.4	34.4
0.7	85.9	85.9	27.50	-02.1	36.7
0.8	89.8	89.8	31.50	-11.0	39.1
0.9	93.7	93.7	35.40	-19.6	41.5
1.0	97.7	97.7	39.30	-28.1	43.8

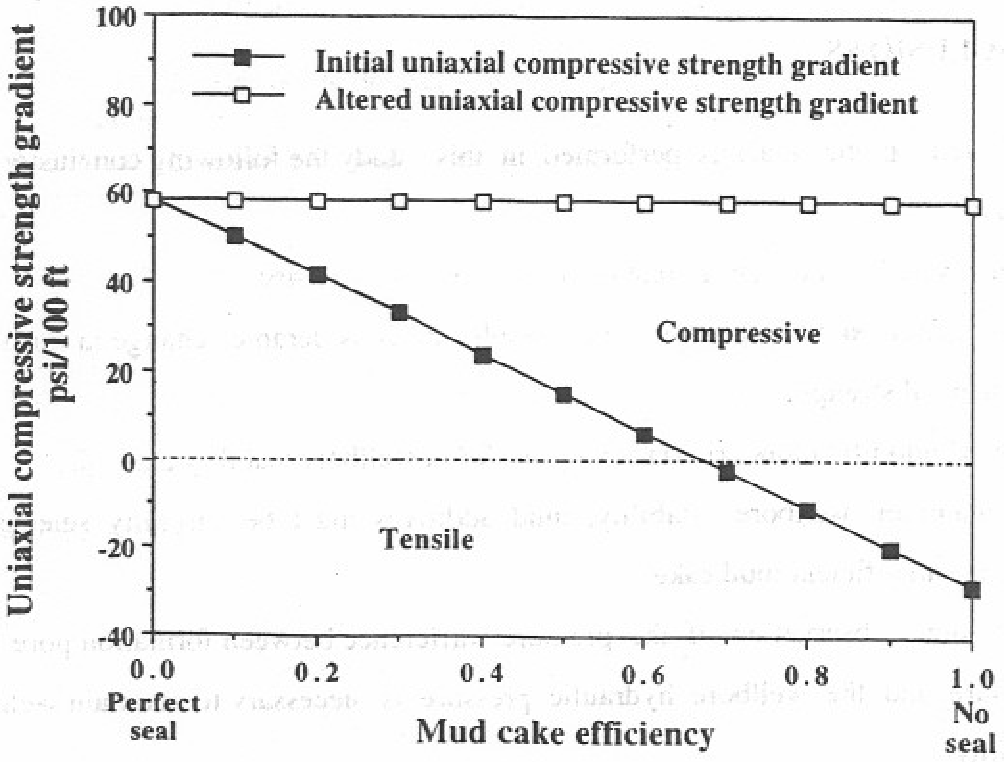


Fig. 4. Effect of mud cake efficiency on formation niaxial compressive strength.

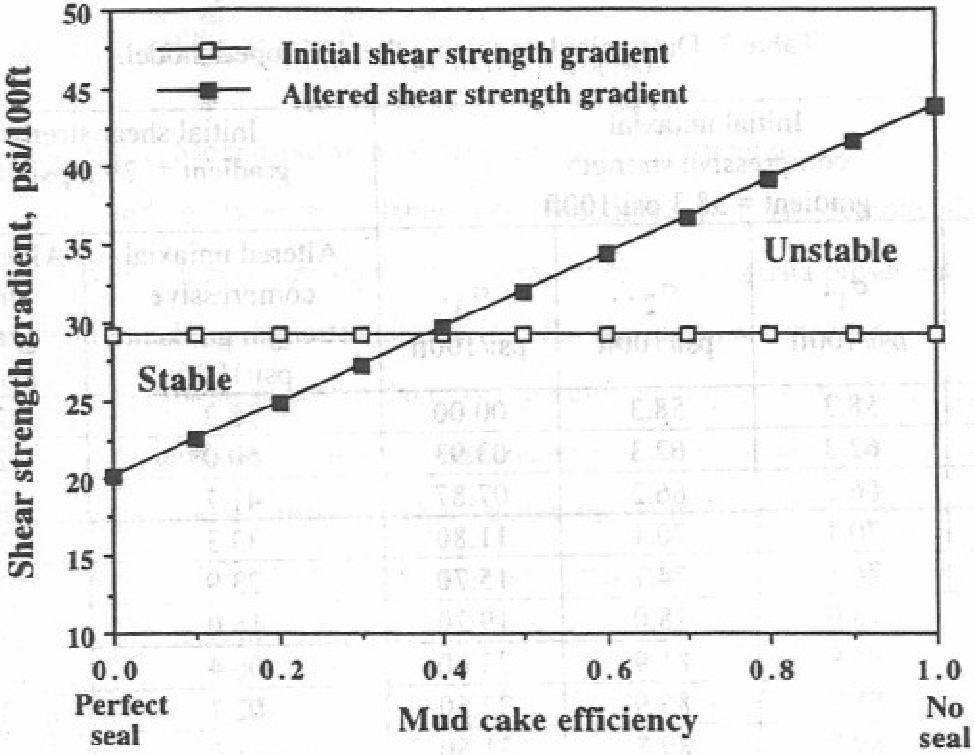


Fig. 5. Effect of mud cake efficiency on formation shear strength.

5. CONCLUSIONS

Based on the analysis performed in this study the following conclusions are drawn out:

I- Mud cake efficiency has a great effect on wellbore stability.

ii- Any change in pore pressure may results in considerable change in formation mechanical strength.

iii- Mohr-Coulomb failure criteria is very useful in wellbore stability analysis.

iv- To maintain wellbore stability, mud additives must be carefully selected to produce an efficient mud cake.

v- Continuous observation of the pressure difference between formation pore fluid pressure and the wellbore hydraulic pressure is necessary to maintain wellbore stability.

vi- In addition to Mohr-Coulomb failure criteria, any other suitable failure criteria can be applied in the developed model.

REFERENCES

1. Musaed N. J. Al-Awad and Smart, B. G. D. "The Effect of Mud Weight and Orientation on the Stability of Inclined Boreholes.", Al-Azhar Engineering Fourth International Conference, Cairo, Egypt, December 16-19, (1995).
2. Ghetham, J. B. "Wellbore Stability.", Journal of Petroleum Technology, pp889-896, June (1994).
3. Chenevert, M. E. "Shale Alteration by Water Adsorption.", Journal of Petroleum Technology, pp1140 -1148, September (1970).
4. Morita, N. and Lee, W. "Rock Mechanics Aspects of Drilling and Completing Highly Inclined Wells in Weak Formations.", SPE 27983 Presented at the University of Tulsa Centennial Petroleum Engineering Symposium held in Tulsa, OK, August 29-31, (1994).
5. Mclean, M. R. and Addis, M. A. "Wellbore Stability: The Effect of Strength Criterion on Mud Weigh Recommen- dations.", SPE 20405, SPE 65th. Annual Technical Conference and Exhibition, New Orleans, LA, September 23-26, (1990).
6. Addis, M. A., Barton, N. R., Bandis, S. C. and Henry, J. P. "Laboratory Studies on the Stability of Vertical and Deviated Boreholes.", SPE 20406,SPE 65th. Annua Technical Conference and Exhibition, New Orleans, LA, September 23-26, (1990).
7. Stien, N. "Estimate Formation Strength Using Log Derived Data.", World Oil, pp 39-40, November, (1987).
8. Twynam, A. J., Collins, M. D., Jackson, M. D. and Forman, P. "Drilling Fluid Programmes Can Reduce Hole Erosion and Minimize Hole Problems: Case Histories Offshore Vietnam.", SPE 30153 presented at SPE PtroVietnam '95 held in Chi Minh City, Vietnam, March 1-3 (1995).

NOMENCLATURE

k = Triaxial stress factor.

P_p = Formation pore pressure.

P_w = Wellbore pressure.

$\Delta P_{mud\ cake}$ = Pressure drop across the mud cake.

ΔP_{total} = Pressure drop across the a system composed of mud cake and the formation in series.

ϕ = Angle of internal friction.
θ = Angular position around the borehole.
ψ = Mud cake efficiency (between 0 and 1).
η = Mud cake sealing coefficient.
σ = Normal (total) stress at failure.
σ_c = Initial uniaxial compressive strength.
$\bar{\sigma}$ = Effective stress.
σ_H, σ_h = Maximum and minimum in-situ horizontal stresses.
$\sigma_x, \sigma_y, \sigma_{zz}$ = Transformed in-situ stress in cartesian form.
$\sigma_r, \sigma_\theta, \sigma_z$ = Induced stresses in polar form.
$\sigma_1, \sigma_2, \sigma_3$ = Induced stresses acting on the borehole.
σ_{1n}, σ_{3n} = Maximum and minimum principal stresses.
ν = Poisson's ratio.
τ_f = Shear strength at failure.
τ_o = Apparent cohesive strength.
$\tau_{xy}, \tau_{xz}, \tau_{yz}$ = Induced shear stresses.
$\tau_{r\theta}, \tau_{rz}, \tau_{\theta z}$ = Induced shear stresses.

دراسة تأثير كفاءة كعكة سائل الحفر على ثباتية البئر أثناء الحفر

عملية الحفر هى الطريقة الوحيدة التى تمكن من الاتصال المباشر بالخزان البترولى ومن الضرورى المحافظة على ثباتية البئر خلال الحفر وبالتالى فإن أى حسابات خاطئة تتسبب فى ضياع البئر ، ومن المعروف أن ثباتية البئر تعتمد على القوة الميكانيكية ومعدل التغير فى الضغط المسامى للصخور المحفورة ولقد وجد أن معدل التغير فى الضغط المسامى يتناسب مع كفاءة كعكة سائل الحفر ، وعلى ذلك فإن أى محاولة لتمثيل ثباتية البئر يجب أن تأخذ بالاعتبار كفاءة كعكةسائل الحفر ، ولقد تم فى هذه الدراسة تطوير أنموذج رياضى يمثل ثباتية البئر العمودى ويأخذ بعين الاعتبار كل من الضغط المسامى لسوائل الطبقات المحفورة والاجهادات الموضعية الأصلية وخواص الطبقات الميكانيكية وكفاءة كعكة سائل الحفر

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