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Investigation Of Factors Affecting The Stability Of Horizontal Oil And Gas Wells

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Abstract

This work provides an elaborated mathematical model to predict the effect of well orientation (azimuth) on the stability of horizontal oil and gas wells. The elaborated model is a combination of the in-situ stress state, formation failure criteria and Kirsch solution for linear-poroelastic materials. The model is then used to investigate different factors affecting the stability of horizontal as well as vertical and inclined wells drilled in strong and weak sandstone formations. Among the investigated factors are pore pressure penetration (as a function of mud cake efficiency), formation mechanical strength and failure criteria. Furthermore, it is shown that horizontal wells drilled parallel to the minimum horizontal principal in-situ stress are the most stable among other horizontal orientations. It was found that the induced shear stresses acting around a borehole can be minimized when sufficient mud weights are used, and that pore pressure penetration (build-up) in the near wellbore formation increases the induced shear stresses acting on the wellbore walls which cause wellbore instability. Induced shear stresses due to pore pressure penetration can be minimized by using a drilling mud that have high filter cake efficiency. Pore pressure penetration, well orientation and wellbore pressure have relatively small effects on the stability of horizontal wells drilled in strong formations compared to those drilled in weak formations.

Introduction

Horizontal well drilling is not a new concept. Interest in the possibility of greatly improving productivity from these wells versus vertically drilled wells in the same fields has been evident since the early 1930[1]. Recently, the major area of application has been in regions where the producing zones are very thin. Drilling highly deviated or horizontal wells within very narrow production zones is done to maximize the contact area of the oil-bearing formations with the wellbore, thereby improving the overall drainage of the reservoir[2]. The benefits gained from drilling high angle and horizontal wells, such as achieving high flow rates and reducing gas and water coning, have been well documented. Many aspects concerning the horizontal well technology have been addressed by researchers such as completion[3], hole cleaning[4], casing design[5], cementing[2], compaction and subsidence[6], sand production[7], formation damage characterization[8], acidizing and fracturing[9]. However, the influence of rock mechanics on highly inclined and horizontal wells is often over-looked during the early stages of reservoir appraisal and development. In weak formations, several factors can have significant impact on drilling and completion operations and hence the overall stability of the well[10]. Generally, wellbore instability is caused by a combination of factors which may be classified as being either controllable or uncontrollable in origin (natural). These factors are summarized in **Table. 1**. This paper aims to study the effect of the controllable factors on the stability of horizontal oil and gas wells by:

(i) elaborating a mathematical model to predict the optimum wellbore orientation with respect to the in-situ principal stresses as well as the critical wellbore pressure (mud weight);

(ii) shedding light on the importance of reservoir rock mechanical properties and failure criteria on the stability of horizontal wells; and

(iii) investigating the effect of pore pressure penetration (build-up) on horizontal wellbore stability.

The Mathematical Model

Two obvious mechanisms causing wellbore failure are shear and tensile failure. One of the widely used failure criterion is the Mohr-Coulomb failure criterion. As is well known, this criterion is defined as follows:

$$\tau_f = \tau_o + \sigma \tan\phi \qquad (1)$$

When a rock is loaded beyond its elastic limit, it deforms (yields). If the yielded rock have a residual strength and supported by a confining pressure, it will remain in place, and a zone of yielded rock will be formed around the wellbore. If there is no support for the yielded rock, it will drop into the wellbore, and part of it will be produced with the reservoir fluids, and the rest will remain in the bottom of the well, requiring a cleaning process to be done. **Fig. 1** shows the Mohr-Coulomb failure criterion for typical weak and strong sandstones used as reservoir rock in the elaborated model. **Table 2** shows hypothetical physical and in-situ data used in the analysis performed in this work. It was clearly demonstrated that pore pressure penetration is directly proportional to the mud cake efficiency [11, 13]. Mud cake efficiency is the ability of a mud cake to isolate the high wellbore pressure from direct contact with formation pore fluid. This is necessary to avoid the transient pore pressure build-up which may reduce formation strength. This effect is clearly appear in Eq. 1 and **Figs. 2 and 3**. Mud cake efficiency (ψ) can be represented mathematically as follows [11]:

$$\psi = \frac{\Delta P_{total} - \Delta P_{mud\ cake}}{\Delta P_{total}} \quad \ldots\ldots(2)$$

Mud cake efficiency then can be used to calculate the magnitude of pore pressure build-up as follows[11]:

$$P_p = P_p + \psi\left[P_w - P_p\right] \quad \ldots\ldots(3)$$

The simplicity with which the wellbore stability can be computed is highly dependent on the stress-strain behavior commonly chosen for modelling the formation response to loading. The most common behavior assumed is that the formation is homogeneous, isotropic and linear poroelastic. These assumptions allow the stresses to be determined from a set of fairly simple equations. More complex models suffer from an extensive list of input parameters, many of which cannot be realistically determined. The equations required to compute the stresses around vertical, inclined or horizontal wells is called Kirsch solution[11-18]. The in-situ principal stresses can be transformed parallel to the wellbore axis by the application of the following matrices (see **Fig. 4**):

$$\begin{bmatrix}\sigma_x\\ \sigma_y\\ \sigma_{zz}\end{bmatrix} = \begin{bmatrix}Cos^2\beta\, Cos^2\alpha & Sin^2\beta\, Cos^2\alpha & Sin^2\alpha\\ Sin^2\beta & Cos^2\beta & 0\\ Cos^2\beta\, Sin^2\alpha & Sin^2\beta\, Sin^2\alpha & Cos^2\alpha\end{bmatrix}\begin{bmatrix}\sigma_H\\ \sigma_h\\ \sigma_v\end{bmatrix} \ldots(4)$$

$$\begin{bmatrix}\tau_{yz}\\ \tau_{xz}\\ \tau_{xy}\end{bmatrix} = \frac{1}{2}\begin{bmatrix}Sin^2\beta\, Sin\alpha & -Sin^2\beta\, Sin\alpha & 0\\ Sin^2\alpha\, Cos\beta & Sin^2\beta\, Sin^2\alpha & -Sin^2\alpha\\ Cos^2\beta\, Sin^2\alpha & -Sin^2\beta\, Cos\alpha & 0\end{bmatrix}\begin{bmatrix}\sigma_H\\ \sigma_h\\ \sigma_v\end{bmatrix} \ldots(5)$$

After the transformation of the in-situ principle stresses to the inclined or horizontal wellbore frame, the induced stresses acting on a wellbore can be calculated as follows:

$$\begin{aligned}
&\sigma_r = P_w\\
&\sigma_\theta = \left(\sigma_x + \sigma_y - P_w\right) - 2\left(\sigma_x - \sigma_y\right)Cos2\theta - 4\tau_{xy}Sin2\theta\\
&\sigma_z = \sigma_{zz} - 2\nu\left(\sigma_x - \sigma_y\right)Cos2\theta - 4\nu\tau_{xy}Sin2\theta \qquad \ldots\ldots(6)\\
&\tau_{r\theta} = \tau_{rz} = 0\\
&\tau_{\theta z} = 2\left[-\tau_{zx}\,Sin\theta + \tau_{yz}\,Cos\theta\right]
\end{aligned}$$

The principal stresses used in the Mohr-Coulomb failure criterion are shown below[13]:

$$\begin{aligned}
&\sigma_1 = \sigma_r = P_w\\
&\sigma_2 = \frac{1}{2}\left(\sigma_\theta + \sigma_z\right) - \frac{1}{2}\sqrt{\left(\sigma_\theta - \sigma_z\right)^2 + 4\tau_{\theta z}} \qquad \ldots\ldots(7)\\
&\sigma_3 = \frac{1}{2}\left(\sigma_\theta + \sigma_z\right) + \frac{1}{2}\sqrt{\left(\sigma_\theta - \sigma_z\right)^2 + 4\tau_{\theta z}}
\end{aligned}$$

The effective induced stresses acting on the wellbore wall can be computed by applying the effective stress principle[11]. In this principle, the effect of pore pressure is considered by subtracting pore pressure magnitude from the total acting stress taking into account Biot's coefficient are given by:

$$\bar{\sigma} = \sigma - b\,P_p \quad \ldots\ldots(8)$$

Knowing the induced stresses distribution around the wellbore, the maximum induced shear stress acting at each point, and the corresponding maximum allowable shear stress can be calculated as follows:

$$\tau_{Max} = \left[\frac{\bar{\sigma}_1 - \bar{\sigma}_3}{2}\right] \quad \ldots\ldots(9)$$

$$\tau_{MC} = \tau_o + \left[\frac{\bar{\sigma}_1 + \bar{\sigma}_3}{2}\right]\tan\phi \quad \ldots\ldots(10)$$

Therefore, one can predict whether or not the rock will fail by comparing the maximum induced shear stress with the maximum allowable shear stress (limit value given by the Mohr-Coulomb failure envelope) as shown in **Fig. 5**.

Results and Discussion

Prior to drilling of a wellbore, formation rock is exposed to an equilibrium in-situ stress field. In-situ stress field at depth consists of three mutually perpendicular independent stresses: one vertical (σ_v) and two unequal horizontal stresses (σ_h and σ_H) as shown in **Fig. 4**. For inclined or horizontal wells, the in-situ stresses are oriented to the stress system acting parallel to the wellbore axis. The drilling of a wellbore requires removing subsurface rock which disturbs the original equilibrium of the in-situ stresses, since the rock surrounding the drilled hole must now carry a part of the load, previously supported by the removed rock. As stated earlier, the pressure exerted by the drilling fluid, fluid-rock interaction, inclination, orientation, mud type, hole exposure time, and surge/swab pressure can significantly alter the stresses imposed on the wellbore. When the redistributed stresses on the wellbore exceed the subsurface formation rock strength, it may become unstable. In this study, only pore pressure penetration, wellbore inclination, wellbore orientation, and formation strength are investigated. Two types of sandstone rocks were considered in this work. The Mohr-Coulomb failure envelopes of these rocks are presented in **Fig. 1**, whereas other mechanical and in-situ data are given in **Table 2**. The principle of effective stress shown in Eqs. 1 and 8, is employed in the present analysis. **Fig. 2** shows how the failure Mohr circle is shifted to the left when pore pressure term is included in the calculations. This shift may cause the rock to fail either in tension or in shear. When high wellbore pressure is applied, mud filtrate may invade the drilled formation in a transient manner leading to formation pore pressure penetration. This change in pore pressure may disturbs the stress state around the wellbore. Pore pressure penetration is a function of mud cake efficiency. Good mud cake quality must be thin, impermeable and strong enough to resist erosion forces that may exist due to drilling fluid circulation. When high quality mud cake exits in the wellbore, pressure drop will take place in the mud cake itself without disturbing the formation pore pressure as shown in **Fig. 3a**. On the other hand, when the drilling mud produces low quality mud cake, the pressure drop will take place inside the drilled formation near the wellbore area causing a dramatic change in the stress state around the wellbore as shown in **Fig. 3b**. The effect of pore pressure penetration on borehole stability is clearly illustrated in **Fig. 6**. In this figure, when the pore pressure increases by 7.57 MPa, instability takes place in well inclinations from 50° to 90°, whereas, with the initial formation pore pressure of 17.43 MPa, all inclinations produce stable wellbores. In this study, a pore pressure increase is modeled by changing the value of mud cake efficiency (ψ) in Eq. 3. Results are given in **Table. 3**. A change in wellbore pressure can lead to serious wellbore instabilities. As shown in **Figs. 7**, **8**, **9** and **10**, a decrease in mud weight by 7 MPa causes wellbore failure in strong sandstone formations. This effect will be even worst in weak formations. Wellbore orientation can highly affect the stability of horizontal wells. As shown in **Figs. 7, 8, 9 and 10**, boreholes drilled parallel to the minimum horizontal in-situ stress (β=90°) are the most stable among other horizontal orientations. For example, in strong sandstone formation (**Figs. 7 and 8**), when a 25 MPa wellbore pressure is applied, a stable horizontal well can be drilled parallel to the minimum horizontal in-situ stress, whereas, it is impossible to keep a horizontal well open using the same wellbore pressure when it is parallel to the maximum horizontal in-situ stress (β=0°). For weak sandstone formations higher wellbore pressure (45 MPa) is required to maintain the stability of horizontal wells drilled parallel to the minimum horizontal principal in-situ stress compared to a well having the same horizontal orientation drilled in strong sandstone formation (**Figs. 9 and 10**). Furthermore, horizontal wellbores require higher wellbore pressures to maintain their stability compared to vertical ones as shown in **Figs. 11 and 12**. This addition in wellbore pressure is required to balance the induced shear stresses caused by the concentration of the existing in-situ stresses acting around the wellbore. The magnitude of these induced shear stresses for vertical and horizontal wells with different orientations are presented in **Table 4**. As seen in **Figs. 11 and 12,** to maintain the stability of horizontal wells drilled in weak sandstone formations, it is necessary to apply wellbore pressures greater than 33 MPa in the studied case. On the other hand, only 28.5 MPa wellbore pressure is required to keep a vertical borehole open and stable if it is drilled in the same formation under the same in-situ conditions. Other factors affecting the stability of oil and gas wells such as rock-fluid interaction, erosion, drillstring vibration, etc. must also be considered.

Conclusions

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

1. Wellbore stability is affected by pore pressure build-up (penetration), due to the increase in the effective vertical principal stress.
2. Horizontal wellbore stability is highly dependent on the mechanical properties and failure criteria of the drilled formation.
3. Wellbore pressure required to keep a vertical borehole open and stable might not be enough to maintain the stability of a horizontal borehole.
4. Mud cake efficiency must be evaluated prior to drilling to avoid pore pressure penetration (build-up) problem.
5. Wellbore stability is highly dependent on well orientation (azimuth).
6. The induced shear stresses acting around a horizontal wellbore oriented parallel to the maximum horizontal principal in-situ stress are 1.7 times greater than those acting

around a horizontal wellbore drilled parallel to the minimum horizontal principal in-situ stress.

7. Wellbores drilled (oriented) parallel to the minimum horizontal principal in-situ stress are the most stable compared to other horizontal orientations.

8. When the near wellbore pore pressure is increased by 7.5 MPa, the induced shear stresses acting on the wellbore walls are increased by 5.5 MPa.

Nomenclature

b = Biot's coefficient.

P_p = Pore fluid pressure, MPa.

P_w = Wellbore pressure, MPa.

α = Wellbore inclination, degree.

β = Wellbore orientation (azimuth), degree.

θ = Angular position, degree.

ΔP_{total} = Pressure drop across the mud cake and formation in series, MPa.

$\Delta P_{mud\ cake}$ = Pressure drop in the mud cake, MPa.

ϕ = Rock angle of internal friction, degree.

ψ = Mud cake efficiency.

σ = Normal stress at failure, MPa.

$\bar{\sigma}$ = Effective stress, MPa.

$\sigma_H, \sigma_h, \sigma_v$ = Virgin in-situ principal stresses, MPa.

$\sigma_x, \sigma_y, \sigma_{zz}$ = In-situ stresses in cartesian form, MPa.

$\sigma_r, \sigma_\theta, \sigma_z$ = Induced stresses in polar form, MPa.

$\sigma_1, \sigma_2, \sigma_3$ = The near wellbore stresses, MPa.

τ_{MC} = Maximum allowable shear stress, MPa.

τ_{Max} = Maximum induced shear stress, MPa.

τ_o = Rock apparent cohesion, MPa.

$\tau_{xy}, \tau_{xz}, \tau_{yz}$ = Induced shear stresses, MPa.

$\tau_{r\theta}, \tau_{rz}, \tau_{\theta z}$ = Induced shear stresses, MPa.

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Table 1 -Causes of wellbore instability.

Uncontrollable factors	Controllable factors
- Natural fractures. - High pore fluid pressure. - Low strength formation. - High in-situ stresses.	- Well inclination. - Drillstring vibration. - Well orientation.(azimuth). - Erosion. - Pore pressure build-up. - Rock-fluid interaction.

Table 2 -In-situ data used as input in this study.

Properties	Strong Sandstone	Weak Sandstone
Angular position (θ), degree	0	0
Inclination angle (α), degree	0-90	0-90
Orientation angle (β), degree	0-90	0-90
Poisson's ratio (v)	0.24	0.22
Formation depth, m	2790	2790
Angle of internal friction (ϕ), degree	24	17
Apparent cohesive strength (τ_o), MPa	23	16.5
Biot's coefficient (b)	1.0	1.0
Pore pressure (Pp), MPa	17.43	17.43
Vertical principal In-situ stress (σ_v), MPa	63.11	63.11
Maximum principal horizontal In-situ stress (σ_H), MPa	53.64	53.64
Minimum principal horizontal In-situ stress (σ_h), MPa	47.33	47.33

Table 3 -Pore pressure-mud cake efficiency relationship calculations.

Initial pore pressure, MPa	Initial Wellbore pressure, MPa	Mud Efficiency factor (ψ)	Pore pressure build-up, MPa	Final pore pressure, MPa
17.43	25	0	0	17.43
17.43	25	0.21	1.57	19
17.43	25	0.60	4.57	22
17.43	25	1.0	7.57	25

$\psi = 0$ for perfect seal and $\psi = 1$ for no seal.

Table 4 -Maximum shear stress for three borehole orientations.

Borehole orientation	Stresses acting around a wellbore		Differential stress, MPa	Comments
Parallel to σ_v (Vertical well)	σ_H	σ_h	53.64 - 47.33 = 6.31	Minimum shear stresses
Parallel to σ_H (Horizontal well)	σ_v	σ_h	63.11 - 47.33 = 15.78	Shear stresses are 2.5 times greater than those in a vertical well and 1.7 times greater than those in a horizontal well drilled parallel to the minimum horizontal principal In-situ stress.
Parallel to σ_h (Horizontal well)	σ_v	σ_H	63.11 - 53.64 = 9.47	Shear stresses are 1.5 times greater than those in a vertical well and 0.67 times lower than those in a well drilled parallel to the maximum horizontal principal In-situ stress.

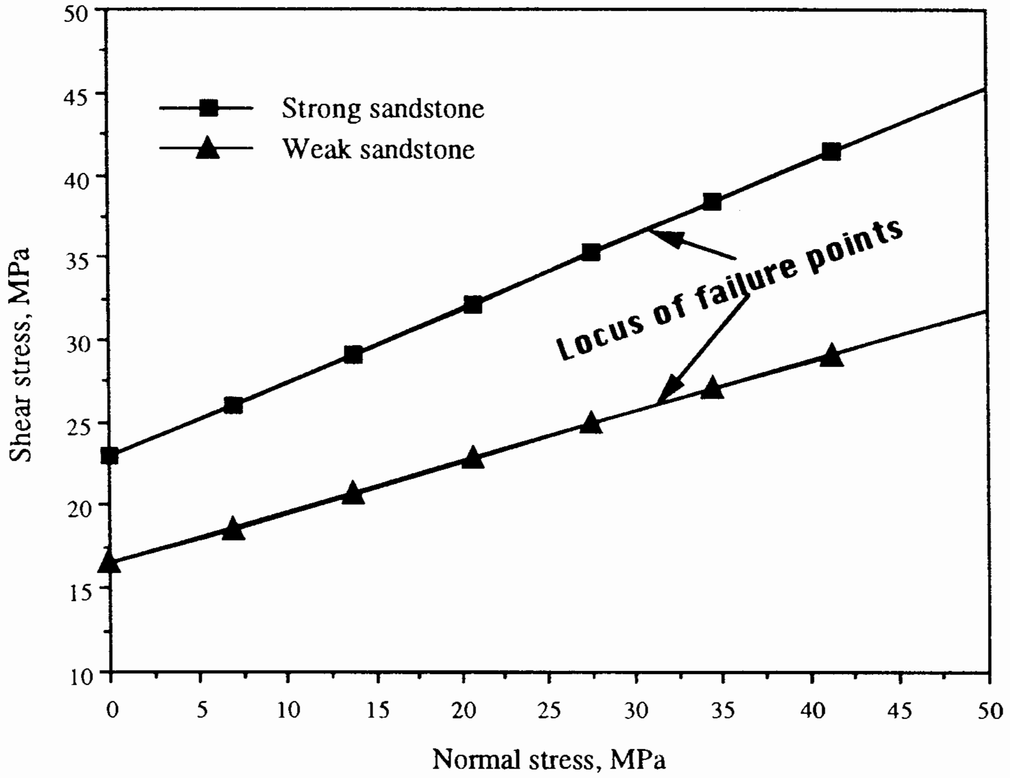


Fig. 1 -Mohr-Coulomb failure envelopes for weak and strong sandtones.

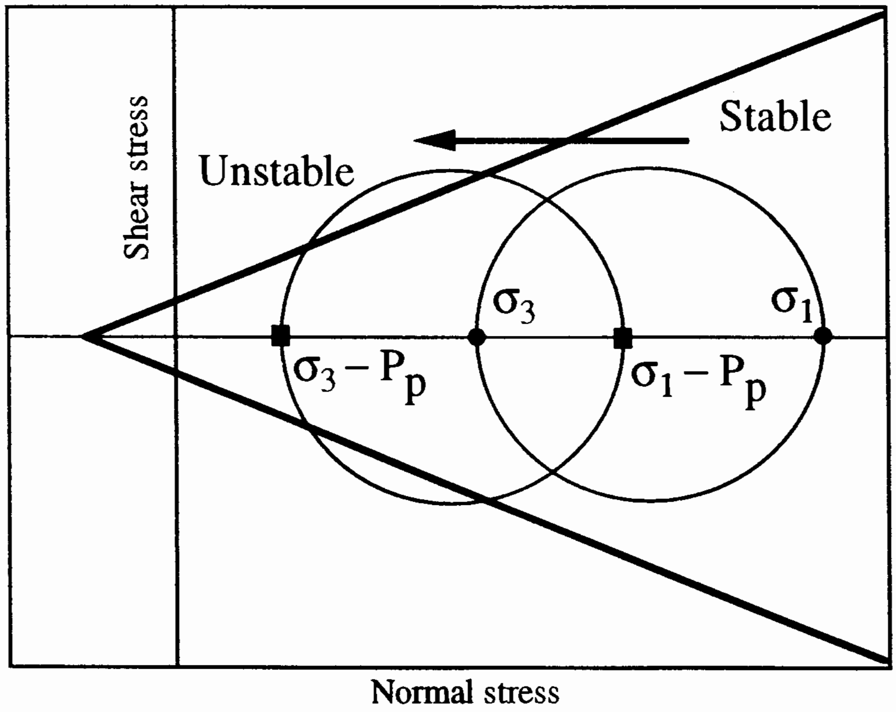
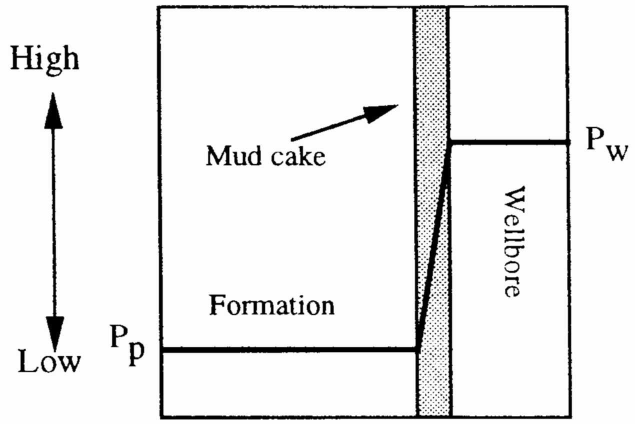
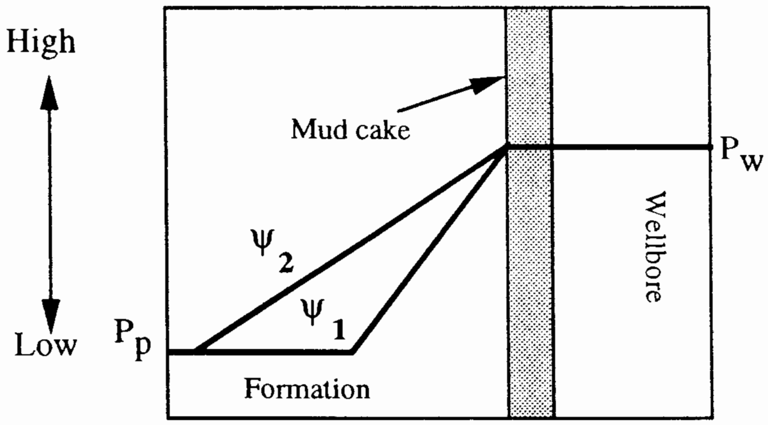


Fig. 2 -Effect of pore pressure increase on rock stability[11].



(a) -High efficiency mud cake.



(b) -Low efficiency mud cake.

Fig. 3 -Effect of mud cake efficiency on pore pressure build-up[11].

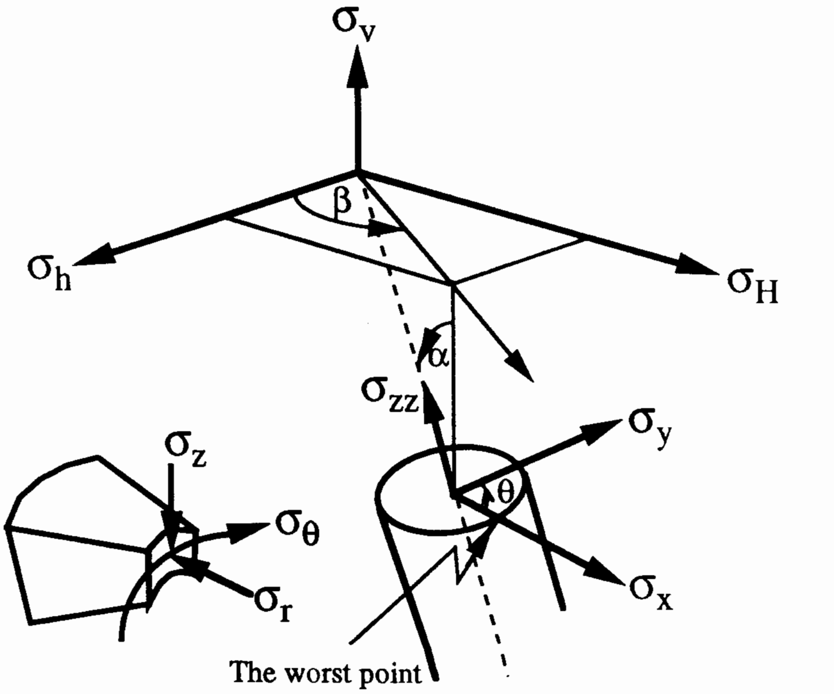


Fig. 4 -Distribution of stresses acting on a deviated well.

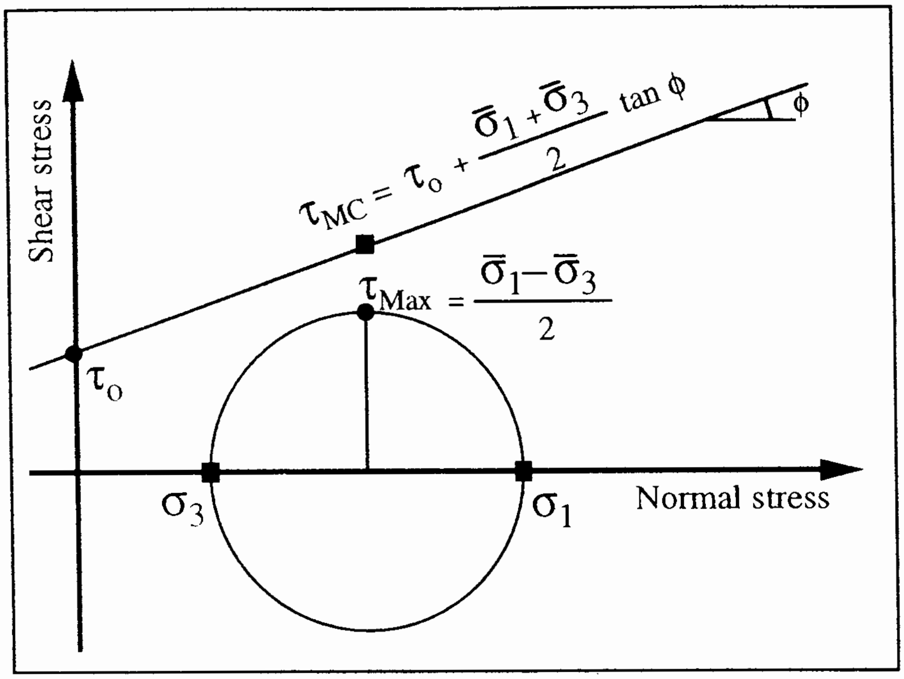


Fig. 5 -Representation of shear stresses acting on the vicinity of a borehole.

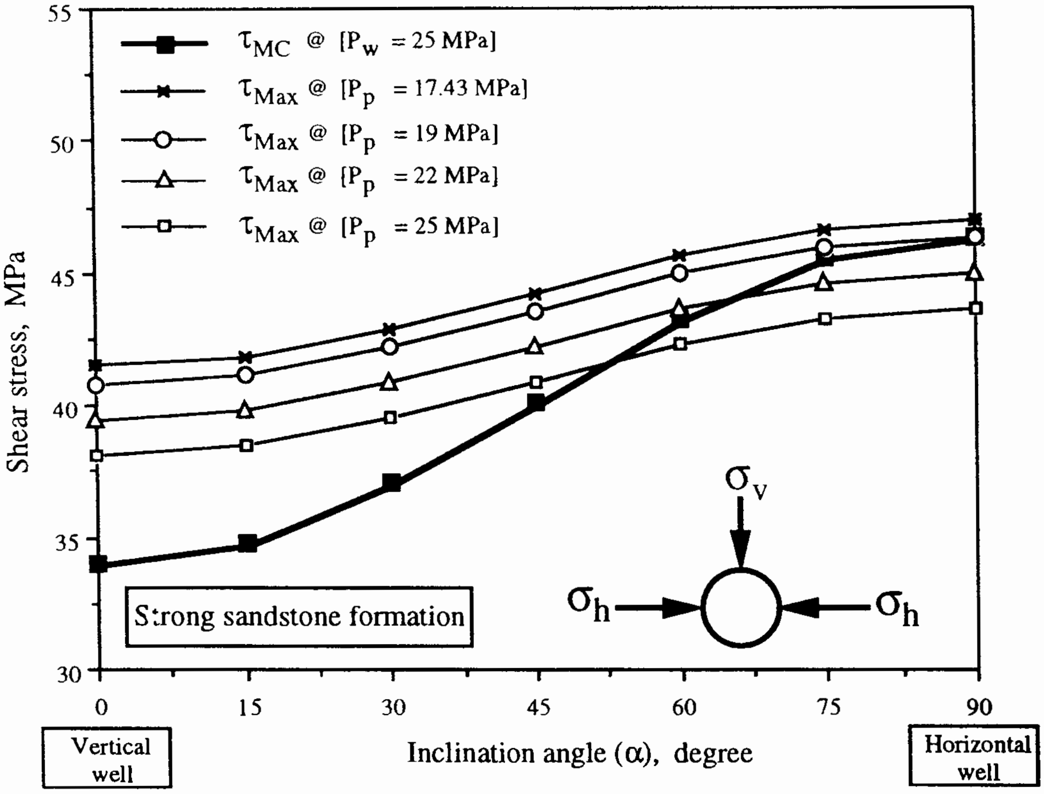


Fig. 6 -Effect of pore pressure penetration and inclination on the stability of wellbores drilled parallel to the maximum horizontal principal In-situ stress (β=0°).

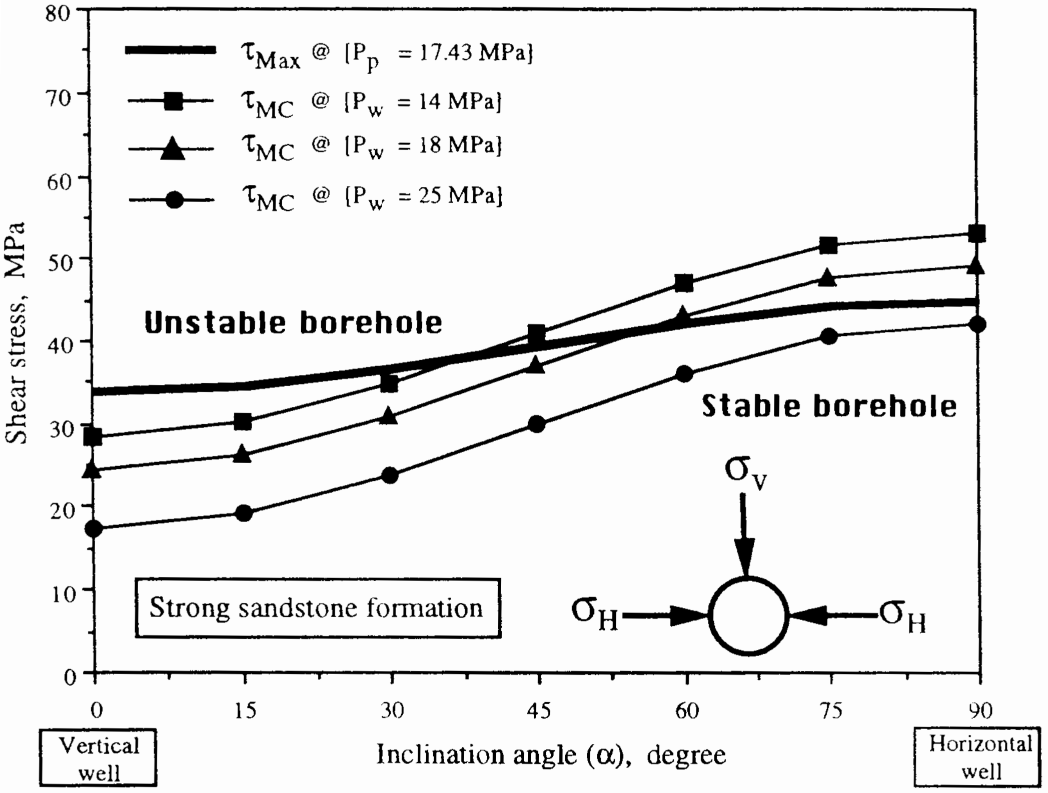


Fig. 7 -Effect of mud weight and inclination on the stability of wellbores drilled parallel to the minimum horizontal principal in-situ stress ($\beta=90^o$).

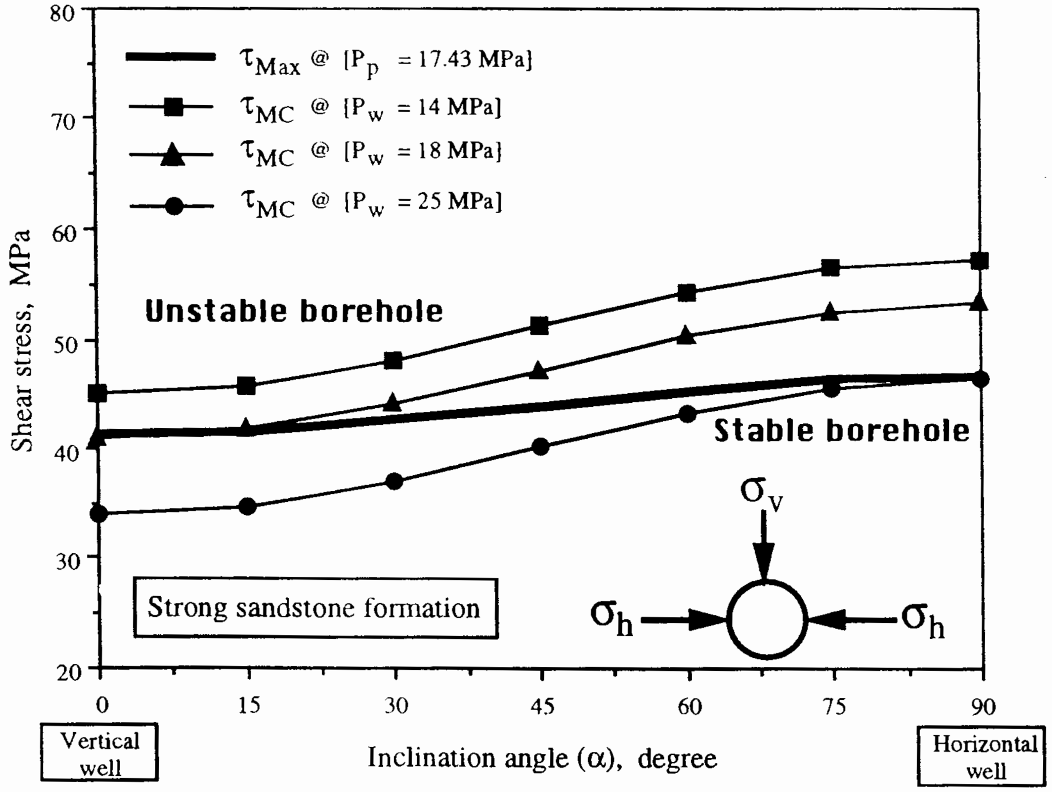


Fig. 8 -Effect of mud weight and inclination on the stability of wellbores drilled parallel to the maximum horizontal principal in-situ stress ($\beta=0^o$).

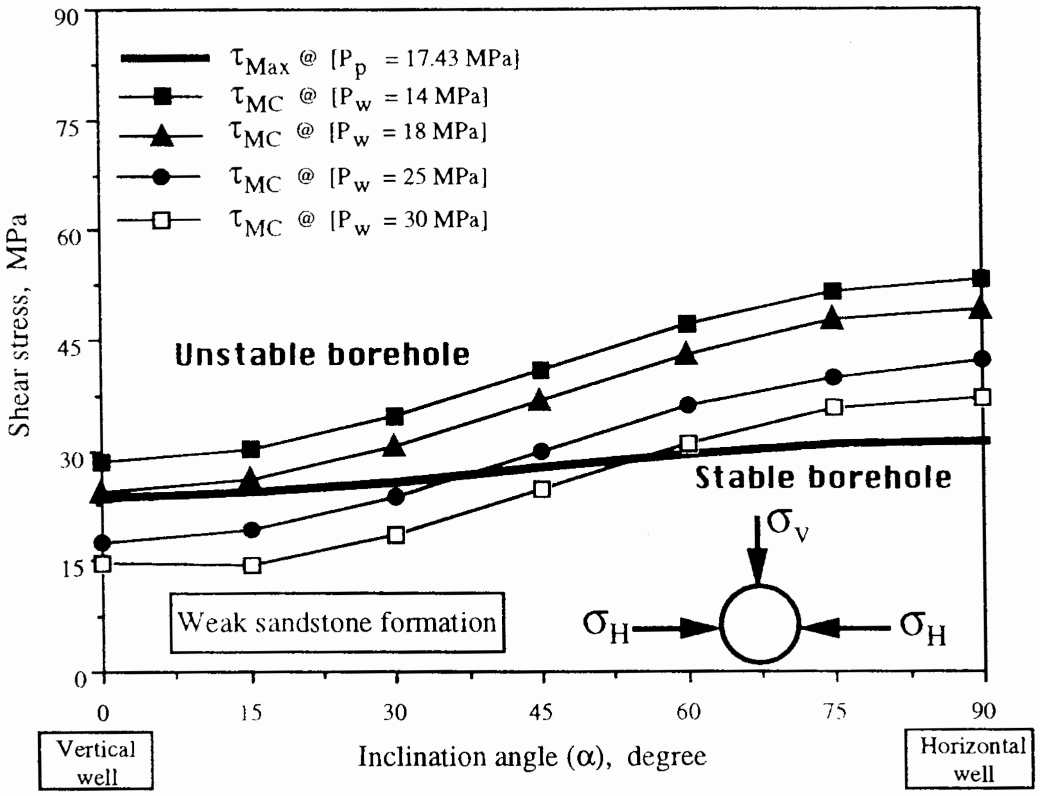


Fig. 9 -Effect of mud weight and inclination on the stability of wellbores drilled parallel to the minimum horizontal principal in-situ stress ($\beta=90^{o}$).

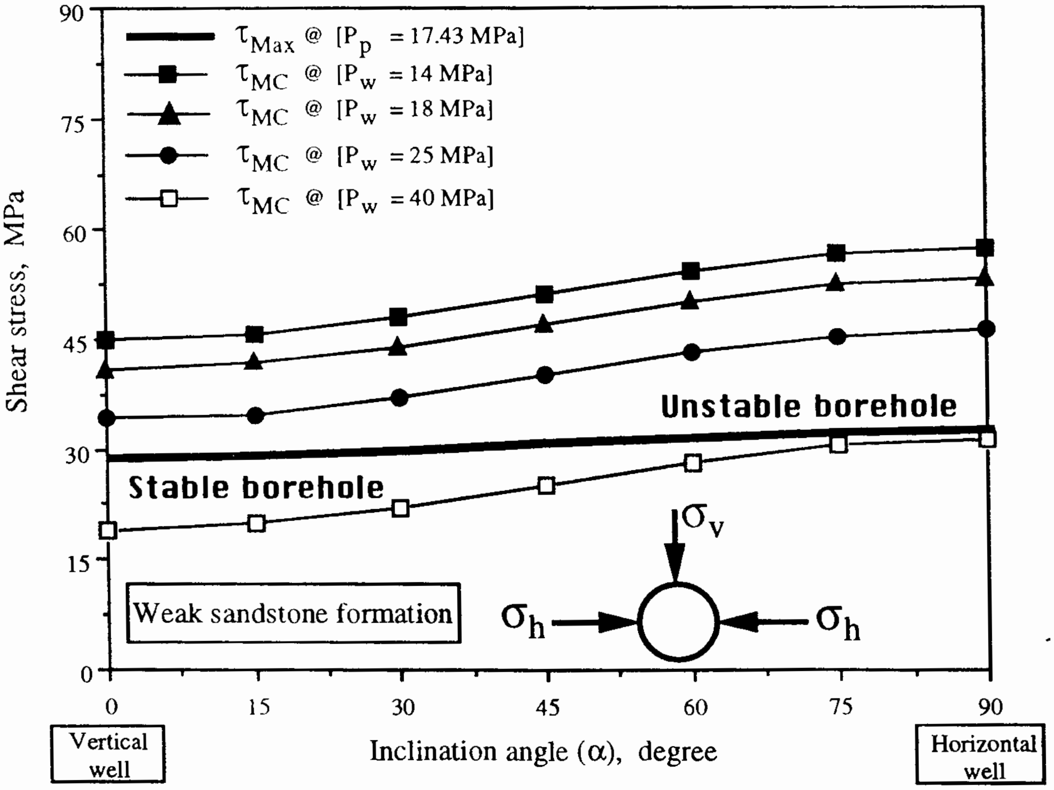


Fig. 10 -Effect of mud weight and inclination on the stability of wellbores drilled parallel to the maximum horizontal principal in-situ stress ($\beta=0^{o}$).

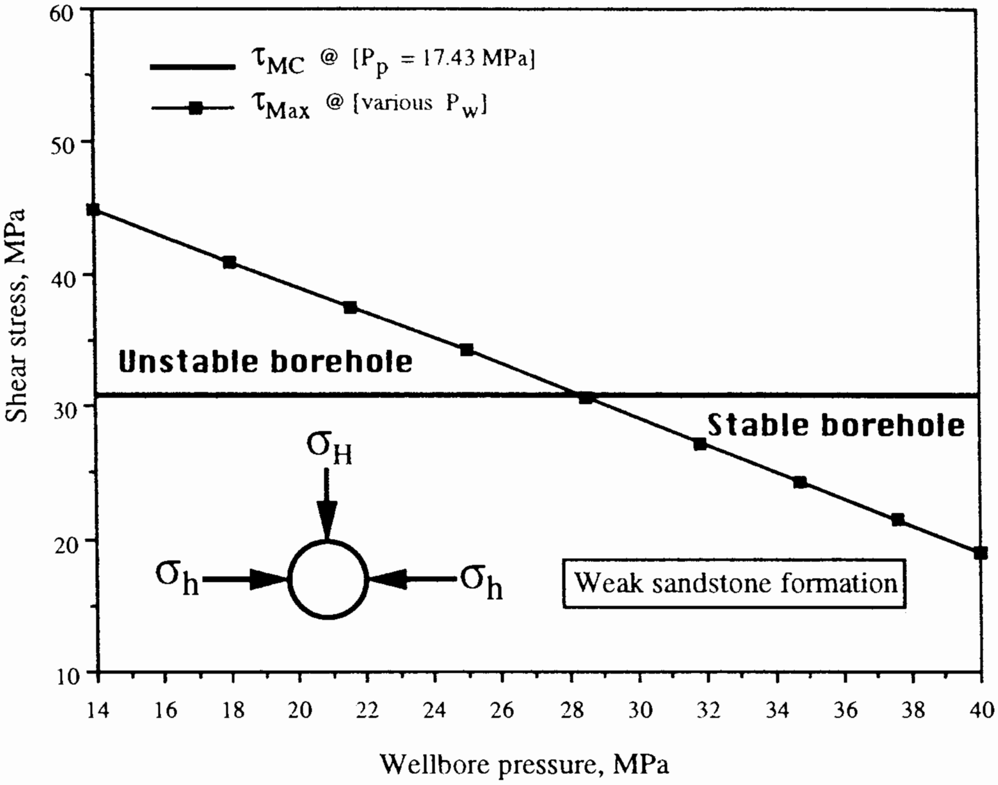


Fig. 11 -Effect of wellbore pressure on the stability of vertical borehole.

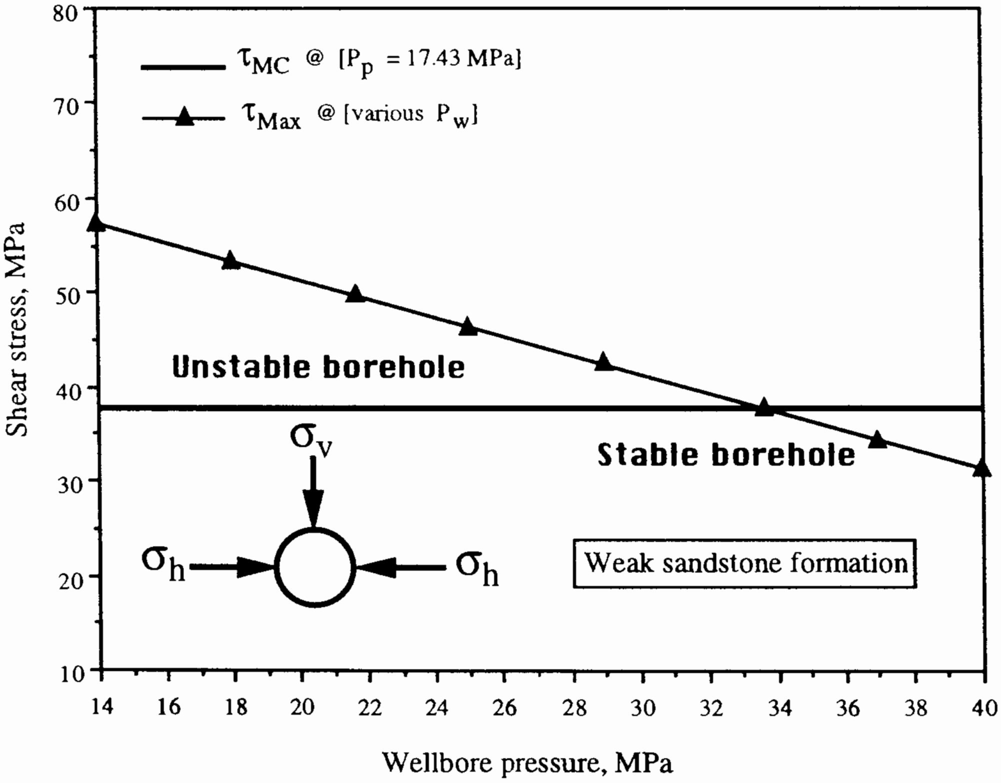


Fig. 12 -Effect of wellbore pressure on the stability of horizontal borehole.