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جامعة الملك سعود
King Saud University
College of Engineering

A Rock Mechanical Model for Overbalanced, Managed Pressure, and Underbalanced Drilling Applications

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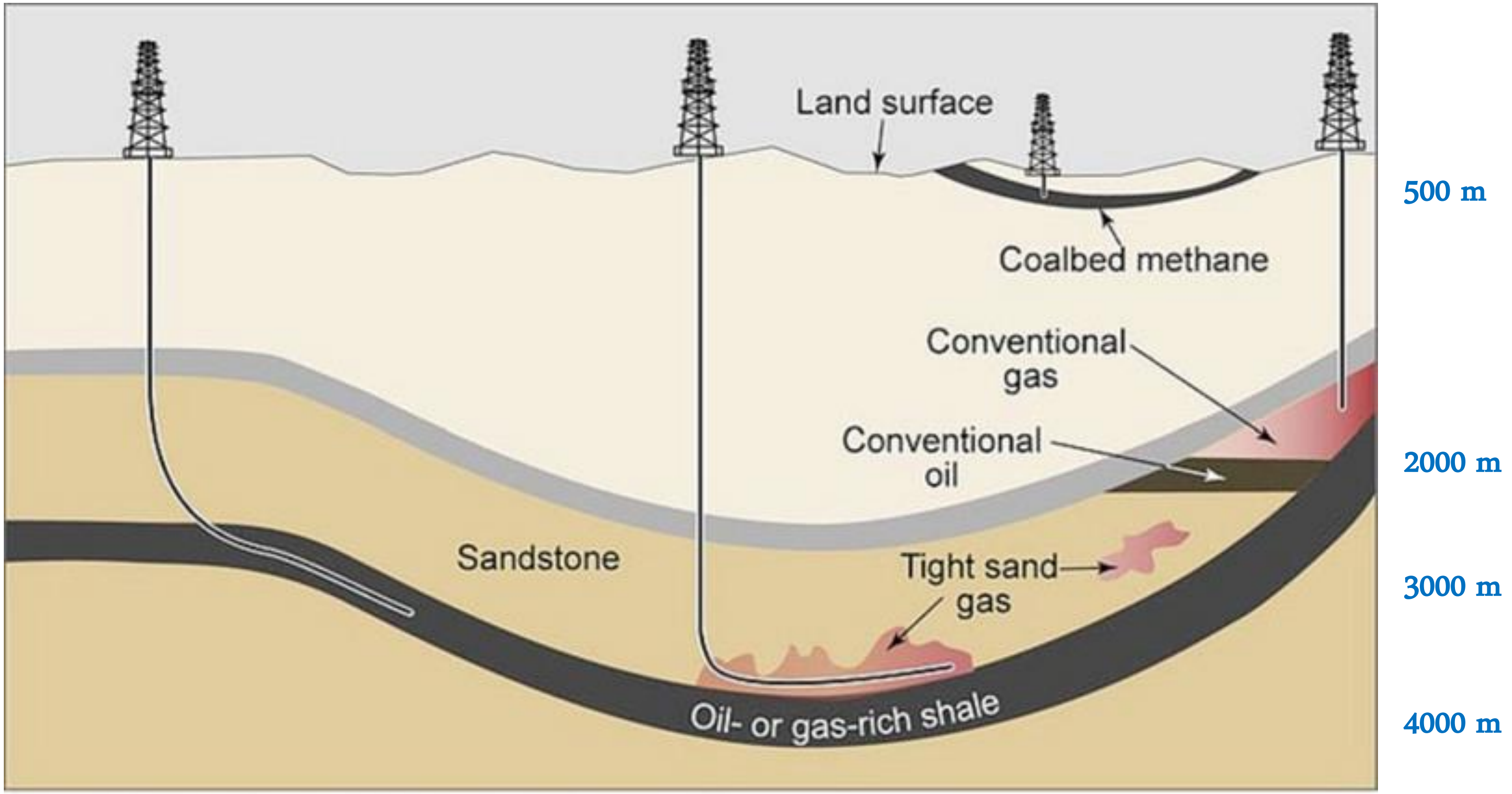
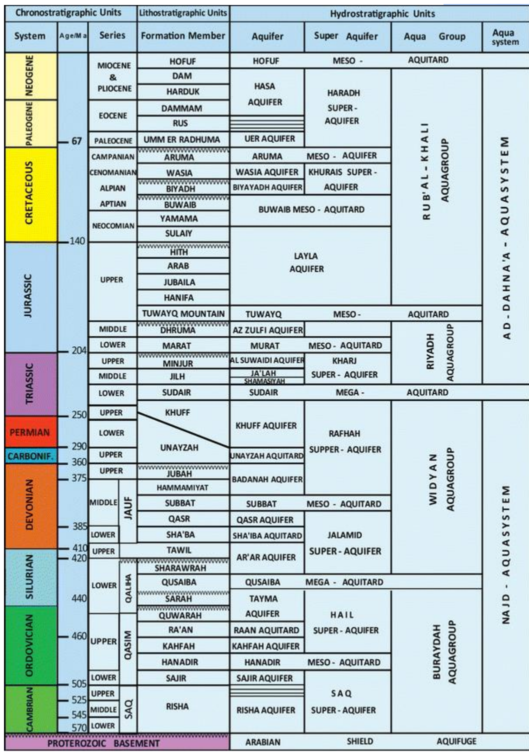
1. OIL & GAS RESERVOIRS



Sources: U.S. Energy Information Administration and U.S. Geological Survey.

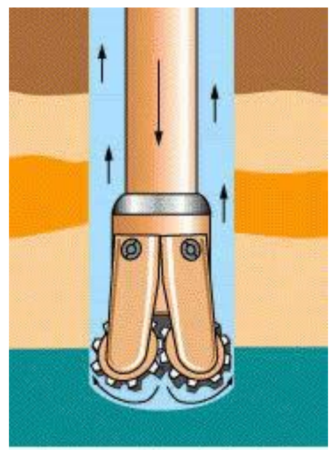
2. OIL WELL DRILLING



Support provided by the removed rock is replaced by the drilling fluid pressure then by the casing and cement

2. WELLBORE STABILITY MANAGEMENT

Formation Pore Pressure & Strength



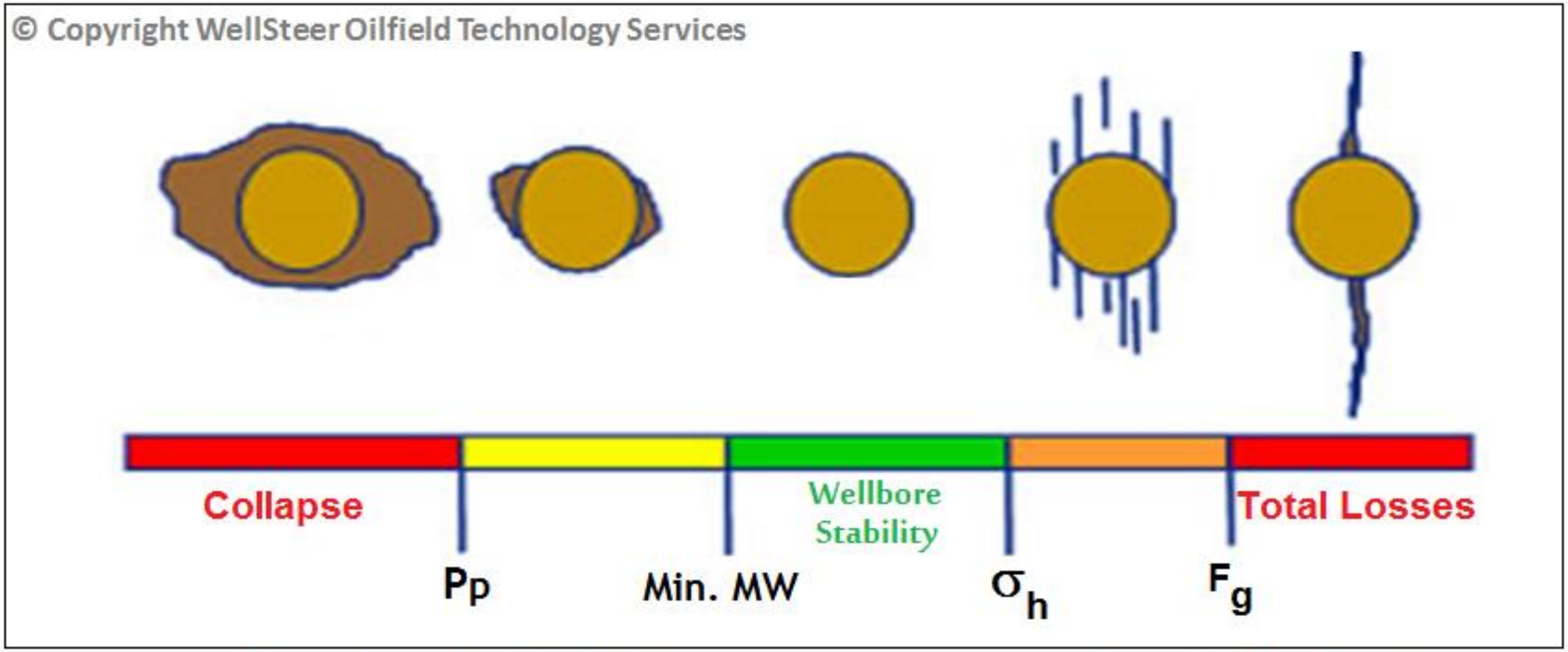
Mud circulation in the hole

Drilling Fluid Pressure & Type

Non-Adjustable

Adjustable

2. WELLBORE INSTABILITY MODES



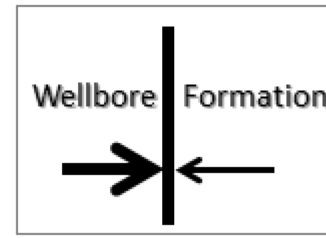
Compressive Failure (Shearing)

Tensile Failure (Fracturing)

3. DRILLING TECHNOLOGY

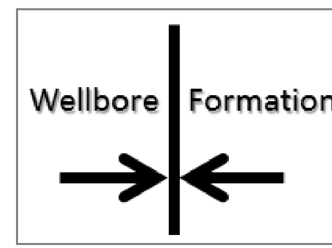
1. Overbalanced Drilling (OBD)

Drilling fluid pressure > Formation pressure



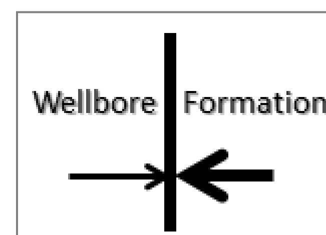
2. Managed Pressure Drilling (MPD)

Drilling fluid pressure = Formation pressure



3. Underbalanced Drilling (UBD)

Drilling fluid pressure < Formation pressure



4. OVERBALANCED DRILLING (OBD)

ADVANTGAES

Its technique and safety issues are very well known, requires fewer personnel to operate, more economical, requires less rig space, provides good borehole stability, and there is no need for handling of hydrocarbons during this type of drilling.

DISADVANTGAES

Potential formation damage, low rate of penetration through harder formations, potential for differential sticking, and potential for getting a kick in case of a section with unknown pore pressures and thief zones.

5. BALANCED DRILLING (MPD)

ADVANTGAES

Avoids the flow of the formation fluids into the wellbore, reduce drilling cost, increase safety, resolve long-lasting drilling problems that contribute to non-productive time such as well instability, stuck pipe, lost circulation, and well control incidents.

DISADVANTGAES

May not be capable of solving the problems encountered, such as when fracture pressure is too close to pore pressure, may not be capable of solving the problems encountered, when variations occur in pore and fracture pressures in different intervals within the same open hole.

6. UNDER BALANCED DRILLING (UBD)

ADVANTGAES

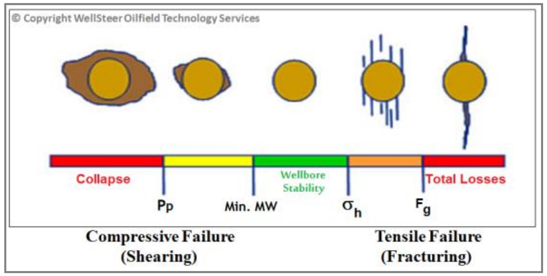
Reducing formation damage in the reservoir, caused by mud solids and liquids invasion and shale swelling, maximizing hydrocarbon production, minimizing lost circulation, increasing drilling rates, extending bit life, and minimizing the need for well stimulation.

DISADVANTGAES

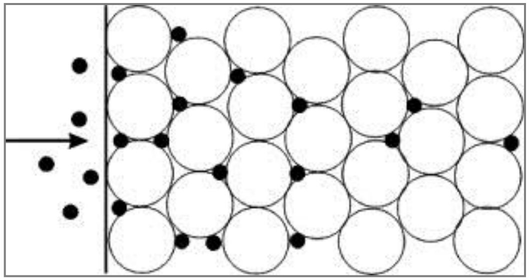
May Well instability and well control issues are big concerns. Drillstring vibrations are often more pronounced, Higher drag and torque will be experienced. complex mixture of fluids and cuttings. Corrosion and ignition potentials. High cost.

7. MPD & UBD APPLICATIONS

It is clear that both MPD and UBD are candidates for drilling oil and gas bearing formations to avoid permeability damage as well as other instability problems when compared to the conventional OBD method.



MPD is normally used in infill drilling in depleted reservoirs where the wellbore stability is the main concern.



UBD is normally used to drill well in newly developed reservoirs when formation damage is a big concern.

8. STUDY OBJECTIVES

The objective of this work is to use:

1. Rock mechanics principles and
2. Laboratory characterization of representative core samples

To elaborate a mathematical model able to predict the wellbore pressure drop, balance, and overbalance (ΔP_w) required for safe UBD, MPD, or OBD.

"A Rock Mechanical Model for

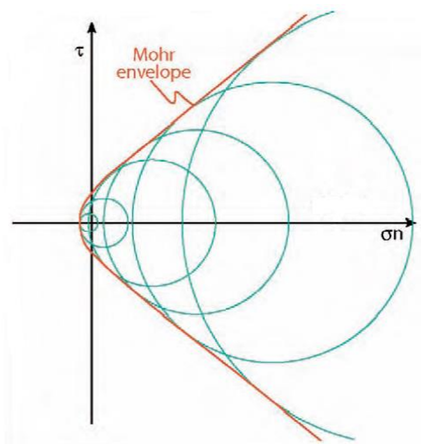
Overbalanced, Managed Pressure, and Underbalanced

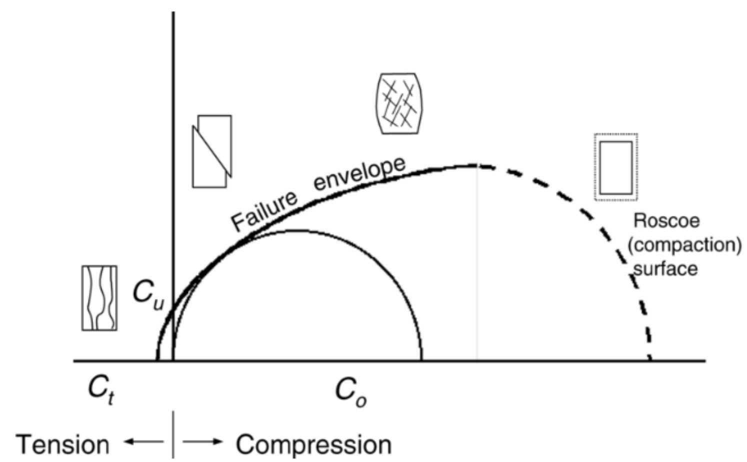
Drilling Applications"

9. THE ELLABORATED MODEL

Formation rock failure criteria are evaluated using Mohr-Coulomb failure criterion which is one of the most famous and applied rock failure criteria (Fjaer et al., 1992). This criterion is shown below:

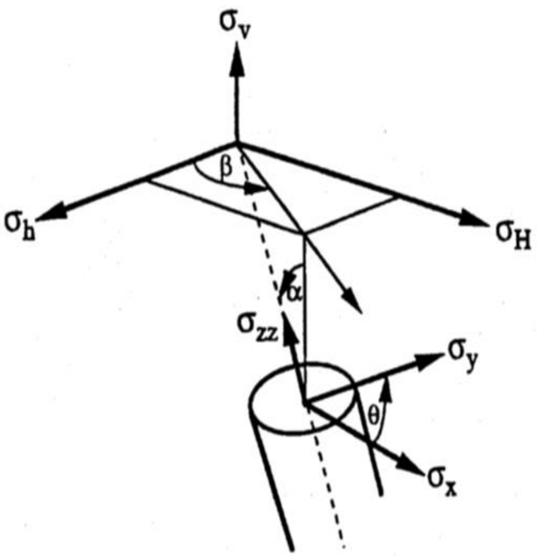
$$\tau_f = \tau_o + \sigma_f \ \mathrm{Tan}\ \phi$$





9. THE ELLABORATED MODEL

Formation Wellbore instability can be predicted when these principal in-situ stresses are transformed parallel to the wellbore axis (for inclined or horizontal wells) using the following matrices (Fjaer et al., 1992):



$$\begin{bmatrix}\sigma_x\\ \sigma_y\\ \sigma_{zz}\end{bmatrix}=\begin{bmatrix}\cos^2\beta\cos^2\alpha & \sin^2\beta\cos^2\alpha & \sin^2\alpha\\ \sin^2\beta & \cos^2\beta & 0\\ \cos^2\beta\sin^2\alpha & \sin^2\beta\sin^2\alpha & \cos^2\alpha\end{bmatrix}\begin{bmatrix}\sigma_H\\ \sigma_h\\ \sigma_v\end{bmatrix}$$

$$\begin{bmatrix}\tau_{yz}\\ \tau_{zx}\\ \tau_{yx}\end{bmatrix}=\frac{1}{2}\begin{bmatrix}\sin 2\beta\sin\alpha & -\sin 2\beta\sin\alpha & 0\\ \sin 2\alpha\cos\beta & \sin^2\beta\sin 2\alpha & -\sin 2\alpha\\ \cos^2\beta\sin^2\alpha & -\sin 2\beta\cos\alpha & 0\end{bmatrix}\begin{bmatrix}\sigma_H\\ \sigma_h\\ \sigma_v\end{bmatrix}$$

9. THE ELLABORATED MODEL

The drilling process generated an induced stresses are acting on the wall of a borehole (Jaeger, 1979). These are, the vertical induced stress (σ_z), the radial induced stress (σ_r) and the tangential induced stress (σ_θ) which can be computed as follows:

$$\bar{\sigma}_r = P_w - P_p = P_{wc}$$

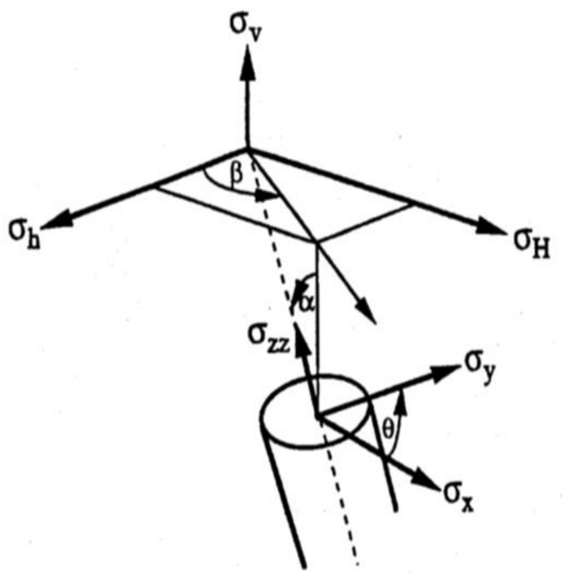
$$\bar{\sigma}_\theta = \left(\sigma_x + \sigma_y - P_p - P_w\right) - 2\left(\sigma_x - \sigma_y\right)\mathrm{Cos}2\theta - 4\tau_{xy}\,\mathrm{Sin}2\theta$$

$$\bar{\sigma}_z = \sigma_{zz} - Pp - 2\nu\left(\sigma_x - \sigma_y\right)\mathrm{Cos}\,2\theta - 4\nu\tau_{xy}\,\mathrm{Sin}2\theta$$

$$\tau_{\theta z} = 2\left[-\tau_{zx}\,\mathrm{Sin}\theta + \tau_{yz}\,\mathrm{Cos}\theta\right]$$

9. THE ELLABORATED MODEL

By knowing the magnitude of the wellbore (mud) pressure, the induced principal stresses acting on the wall of a borehole can be computed as follows:



$$\bar{\sigma}_1 = \sigma_r = P_w - P_p = P_{wc}$$

$$\bar{\sigma}_2 = \frac{1}{2}(\sigma_\theta + \sigma_z) - \frac{1}{2}\sqrt{(\sigma_\theta - \sigma_z)^2 + 4\tau_{\theta z}}$$

$$\bar{\sigma}_3 = \frac{1}{2}(\sigma_\theta + \sigma_z) + \frac{1}{2}\sqrt{(\sigma_\theta - \sigma_z)^2 + 4\tau_{\theta z}}$$

9. THE ELLABORATED MODEL

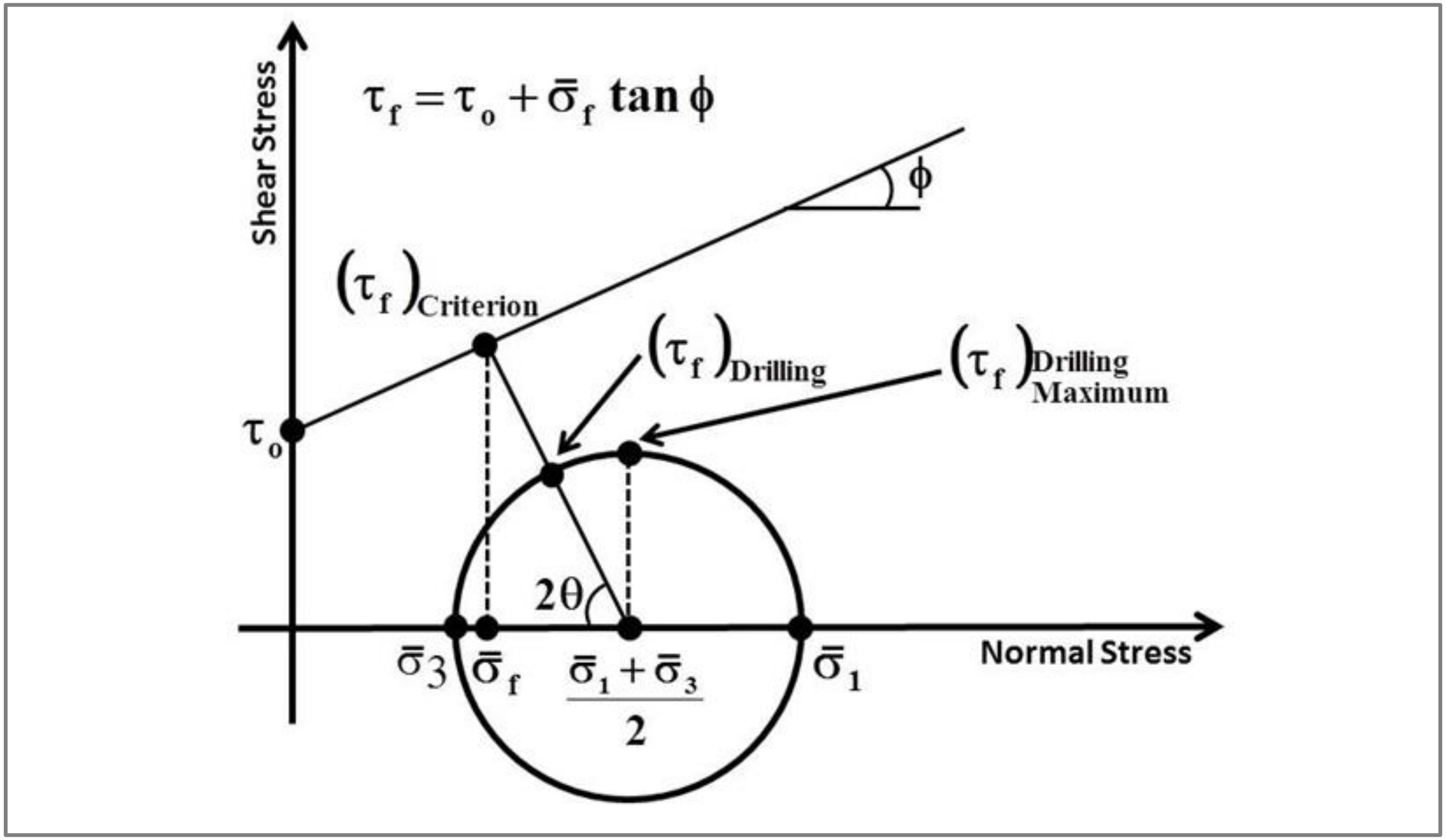
Borehole instability using underbalanced drilling can be predicted by comparing the computed drilling induced and the experimentally measured shear stresses (i.e. failure criterion) as follows:

$$\left((\tau_f)_{Drilling}\right)_{Maximum} = \left[\frac{\bar{\sigma}_1 - \bar{\sigma}_3}{2}\right]$$

$$\left((\tau_f)_{Drilling}\right)_{Criterion} = \left[\frac{\bar{\sigma}_1 - \bar{\sigma}_3}{2}\right] \mathrm{Sin}\, 2\theta$$

$$(\tau_f)_{Ctiterion} = \tau_o + \left[\left(\frac{\bar{\sigma}_1 + \bar{\sigma}_3}{2}\right) + \left(\frac{\bar{\sigma}_1 - \bar{\sigma}_3}{2}\right) \mathrm{Cos}\, 2\theta\right] \tan\phi$$

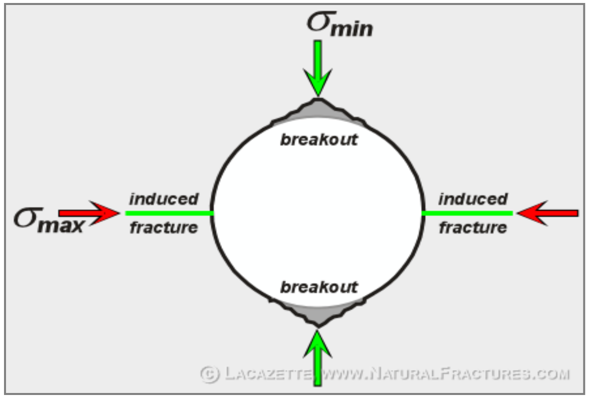
9. THE ELLABORATED MODEL



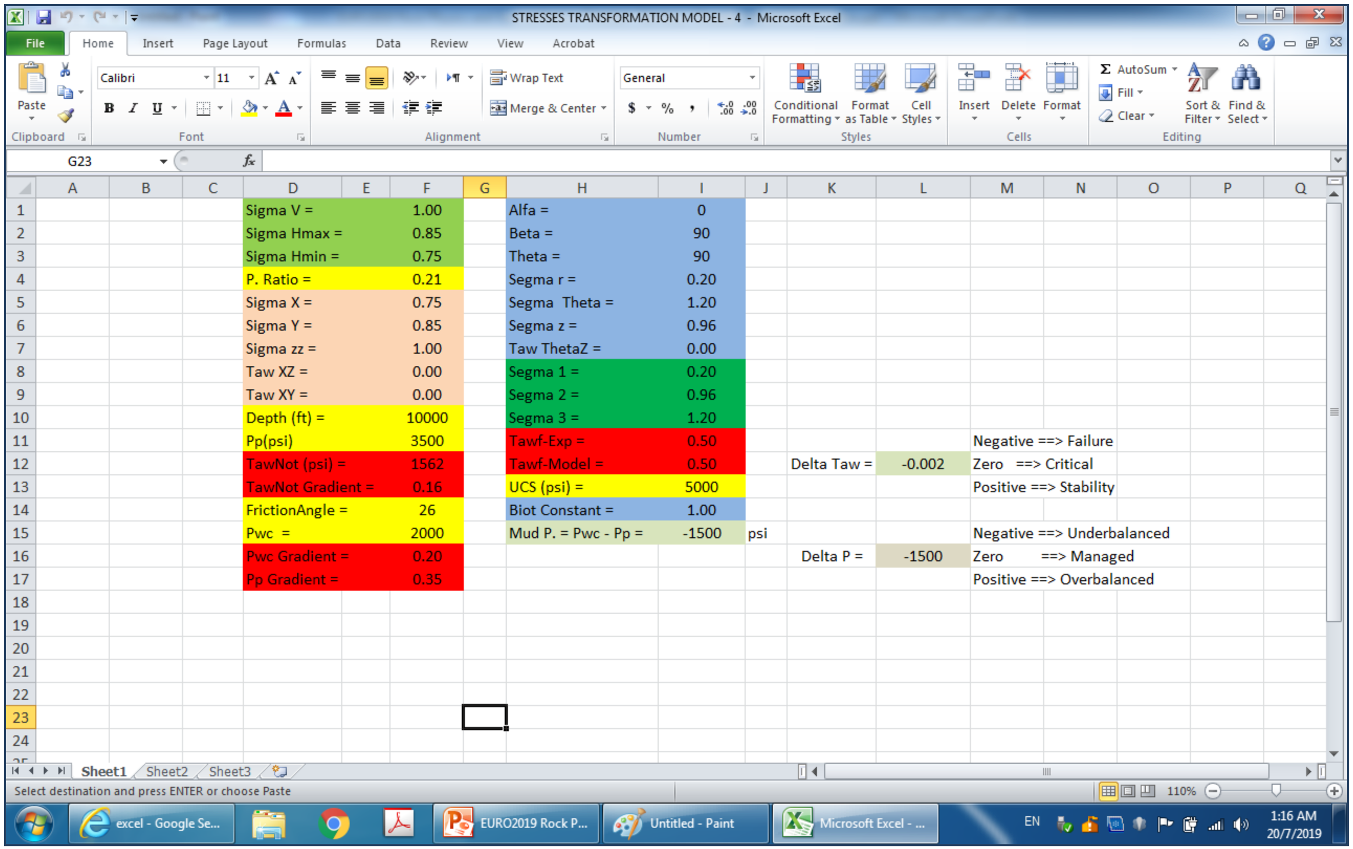
9. THE ELLABORATED MODEL

Wellbore fracturing pressure limit can be estimated using the following relationship (Brady et al., 1985):

$$(P_W)_{\text{Fracturing}} = \left[\frac{2\,\tau_O \operatorname{Cos}\phi}{1+\operatorname{Sin}\phi}\right]$$



9. THE ELLABORATED MODEL



	D	F	H	I	J	K	L	M
1	Sigma V =	1.00	Alfa =	0				
2	Sigma Hmax =	0.85	Beta =	90				
3	Sigma Hmin =	0.75	Theta =	90				
4	P. Ratio =	0.21	Segma r =	0.20				
5	Sigma X =	0.75	Segma Theta =	1.20				
6	Sigma Y =	0.85	Segma z =	0.96				
7	Sigma zz =	1.00	Taw ThetaZ =	0.00				
8	Taw XZ =	0.00	Segma 1 =	0.20				
9	Taw XY =	0.00	Segma 2 =	0.96				
10	Depth (ft) =	10000	Segma 3 =	1.20				
11	Pp(psi)	3500	Tawf-Exp =	0.50				Negative ==> Failure
12	TawNot (psi) =	1562	Tawf-Model =	0.50		Delta Taw =	-0.002	Zero ==> Critical
13	TawNot Gradient =	0.16	UCS (psi) =	5000				Positive ==> Stability
14	FrictionAngle =	26	Biot Constant =	1.00				
15	Pwc =	2000	Mud P. = Pwc - Pp =	-1500	psi			Negative ==> Underbalanced
16	Pwc Gradient =	0.20				Delta P =	-1500	Zero ==> Managed
17	Pp Gradient =	0.35						Positive ==> Overbalanced

Microsoft Excel Spreadsheets for the Elaborated Model

10. INPUT DATA

Hypothetical data used to validate the mathematical model and to predict the wellbore pressure required for safe UBD, MPD, and OBD operations from wellbore instability prospects. These data are a modification of a real case vertical oil well in china (Qiang, 2015).

Table 1 Hypothetical data used for model verification

Rock Type	ISRM Grade	UCS, MPa	Poisson's Ratio	Friction Angle, (Degree)	Depth, m	Pore Pressure, Pp, MPa
Very Weak	R1	6.9	0.20	21	2730	51
Weak	R2	20.6	0.23	26	2730	51
Medium Strong	R3	35.6	0.25	31.4	2730	51
Principal In-Situ Stresses Gradients, psi/ft (MPa/m)				σ_V	1.10	(0.025)
				σ_H	1.00	(0.023)
				σ_h	0.93	(0.021)
Angular Position around the Wellbore, degree				θ	Zero	
Wellbore Inclination from Vertical, degree				α	Zero or 90	
Wellbore Orientation Angle from, degree				β	Zero or 90	

11. COMPUTED DATA
(R1, R2, and R3 Rock Types)

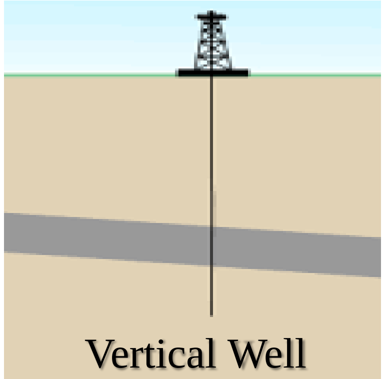


Table 2 Summary of the results of drilling vertical hypothetical wells in R1, R2 and R3 formations

Formation Type	Well Type	UCS, MPa	Poisson's Ratio	Friction Angle, Degree	Safe Drilling Window, MPa					
					OBD		MPD		UBD	
					$P_{wc}=(P_w-P_p)$	P_w	$P_{wc}=(P_w-P_p)$	P_w	$P_{wc}=(P_w-P_p)$	P_w
Very Weak (R1)	Vertical	6.9	0.20	21	+3.2	54.2	0	51	-19.4	31.6
Weak (R2)	Vertical	20.6	0.23	26	+8.1	59.1	0	51	-29.2	21.8
Med. Strong (R3)	Vertical	35.6	0.25	31.4	+11.2	62.2	0	51	-39.9	11.1

12. RESULTS AND DISCUSSION

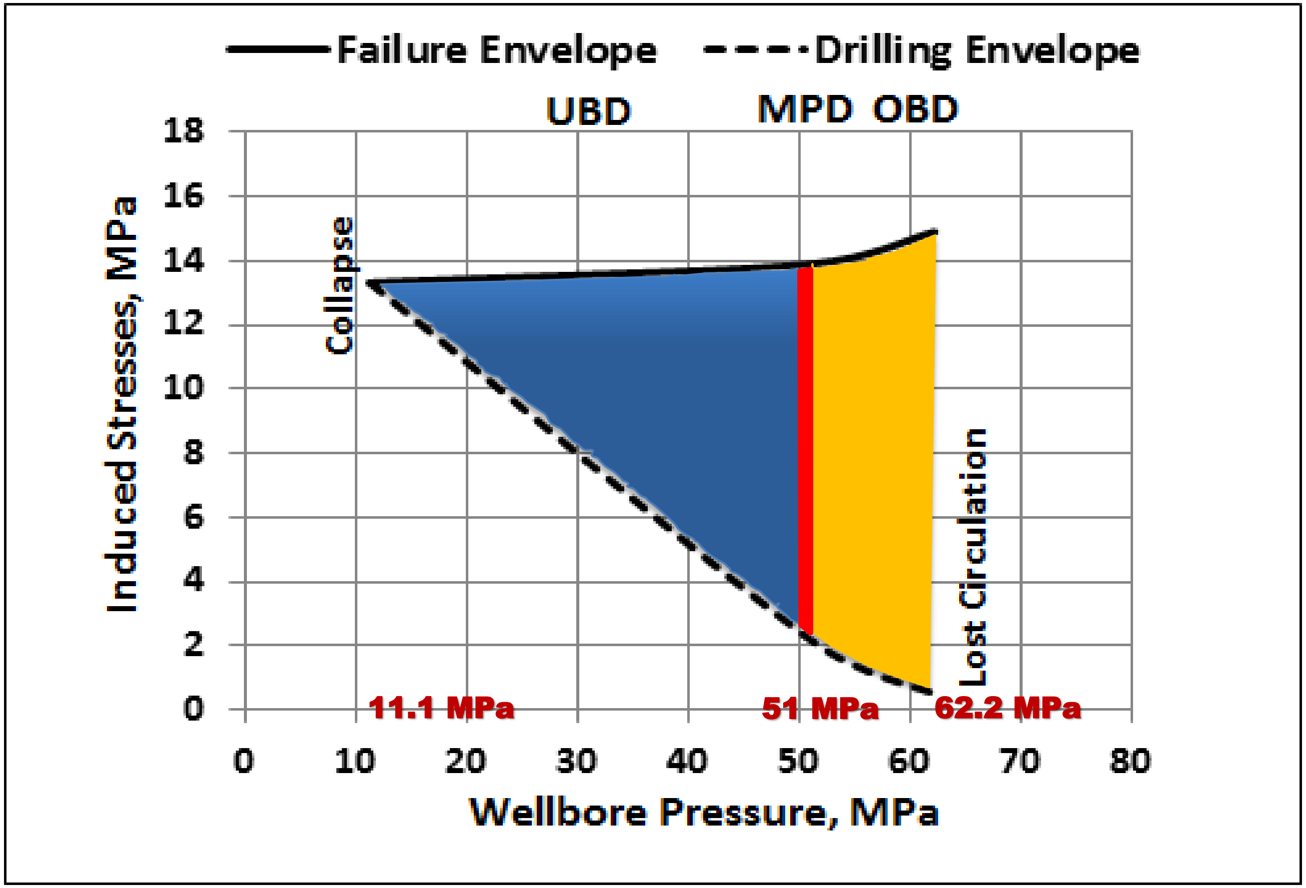


Fig. 6 Vertical well in moderately strong formation (R3)

12. RESULTS AND DISCUSSION

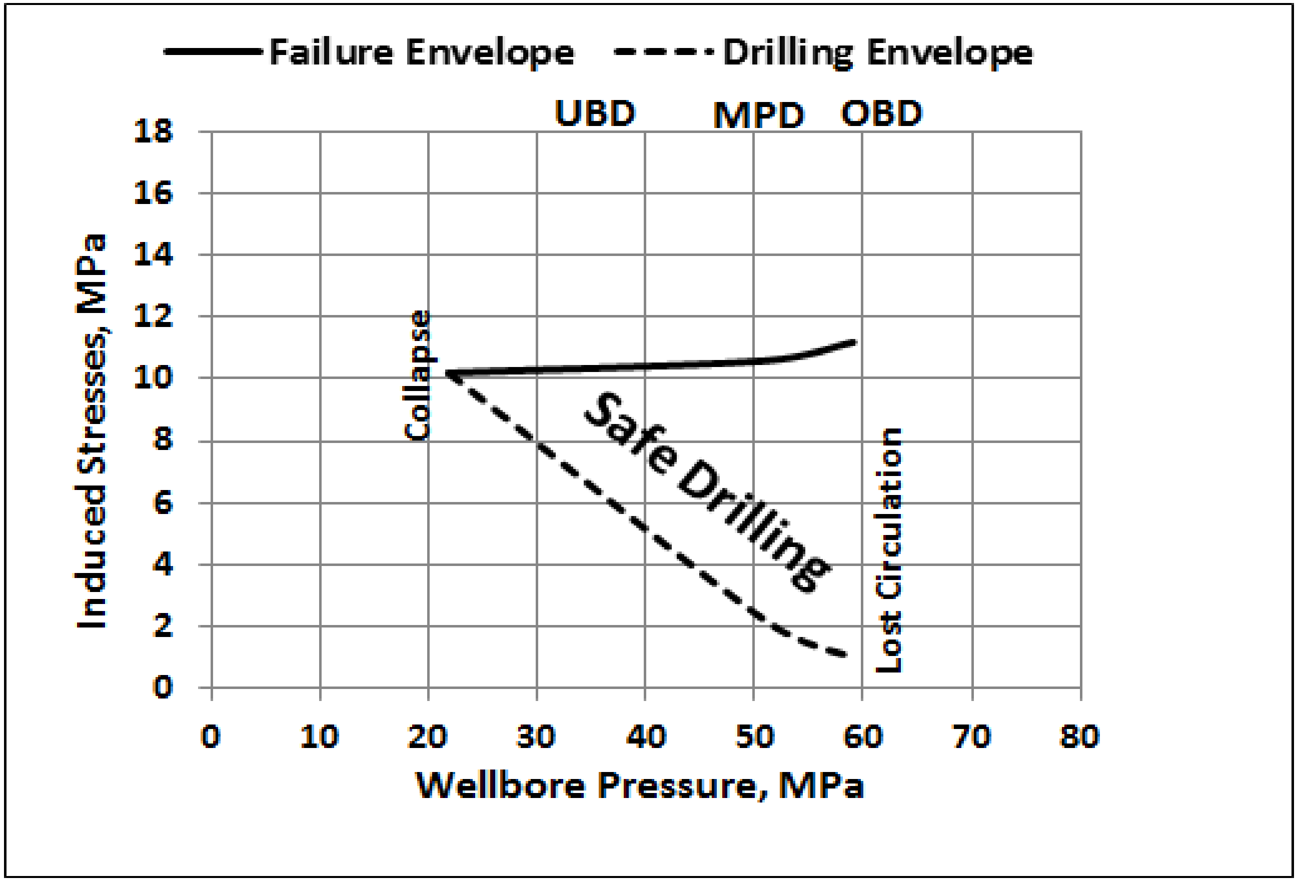


Fig. 5 Vertical well in weak formation (R2)

12. RESULTS AND DISCUSSION

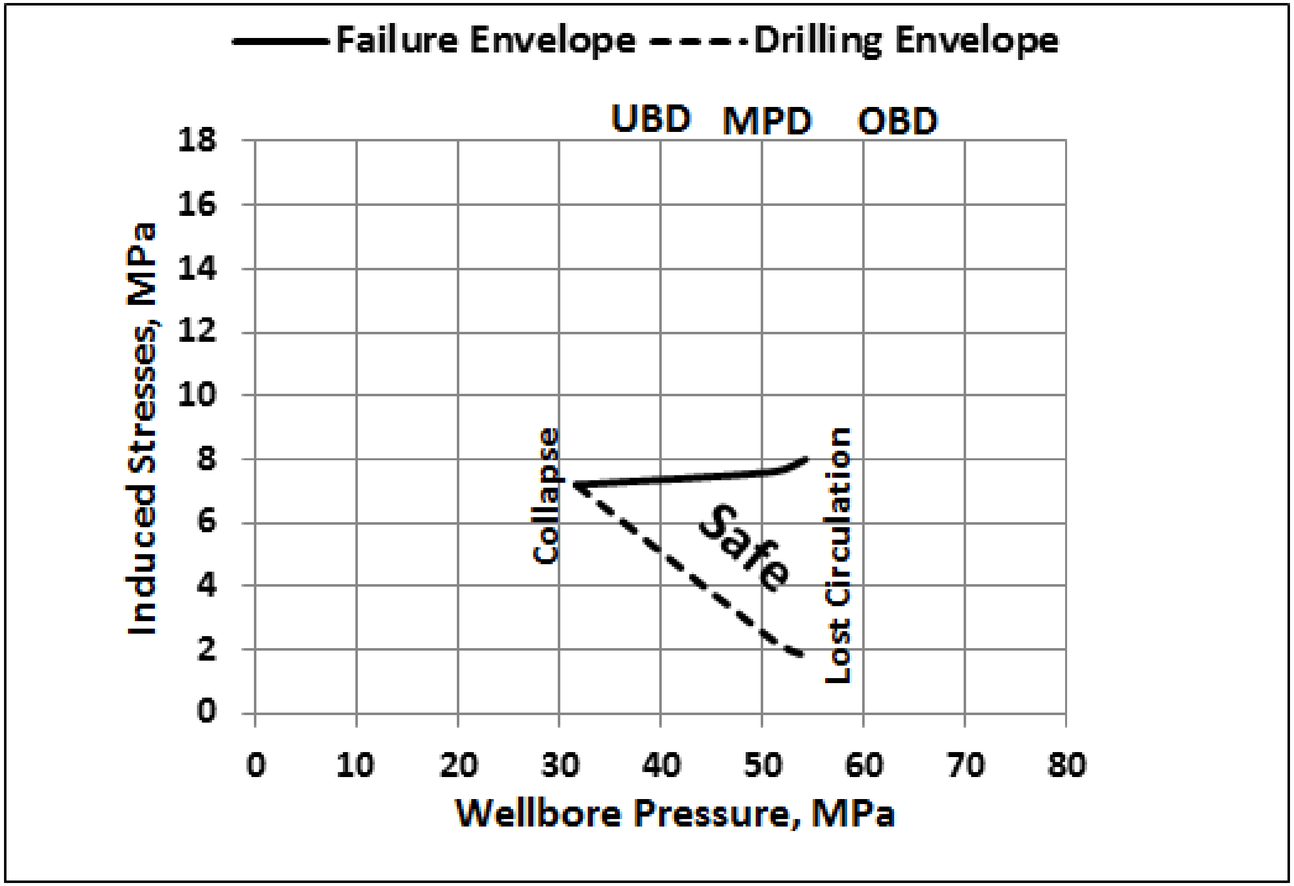


Fig. 4 Vertical well in very weak formation (R1)

12. RESULTS AND DISCUSSION

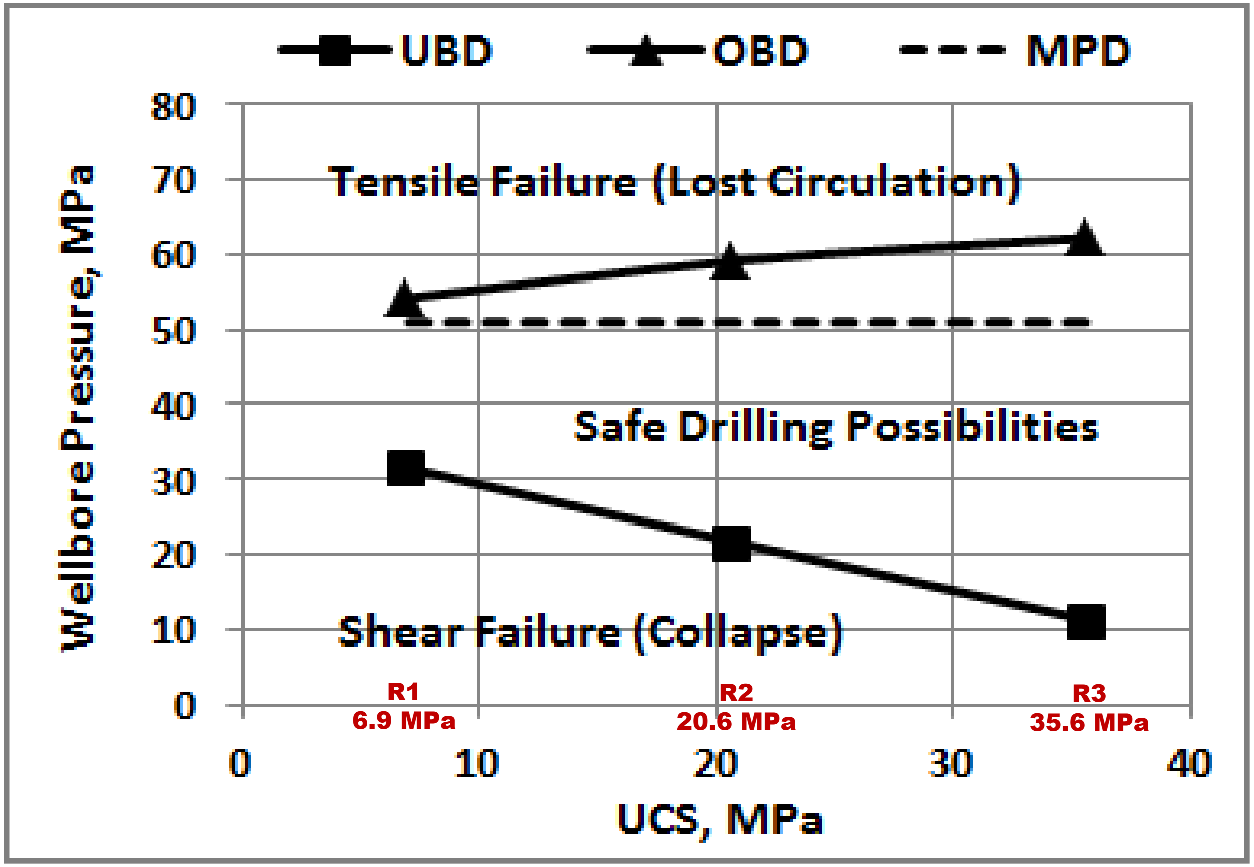


Fig. 7 Summary of the studied vertical drilling cases

13. COMPUTED DATA
(Medium Strong Rock – R3)

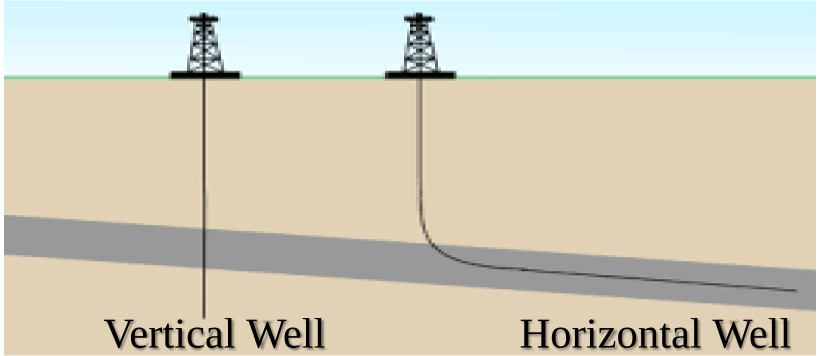


Table 5 Summary of the results of drilling vertical and horizontal hypothetical wells in R3 formation

Formation Type	Well Type	UCS, MPa	Poisson's Ratio	Friction Angle, Degree	Safe Drilling Window, MPa					
					OBD		MPD		UBD	
					$P_{wc} = (P_w - P_p)$	P_w	$P_{wc} = (P_w - P_p)$	P_w	$P_{wc} = (P_w - P_p)$	P_w
Medium Strong (R3)	Vertical	35.6	0.25	31.4	+11.2	62.2	0	51	-39.9	11.2
	Horizontal// σ_h	35.6	0.25	31.4	+11.2	62.2	0	51	-38.2	12.8
	Horizontal// σ_H	35.6	0.25	31.4	+11.2	62.2	0	51	-33.3	17.7

14. RESULTS AND DISCUSSION

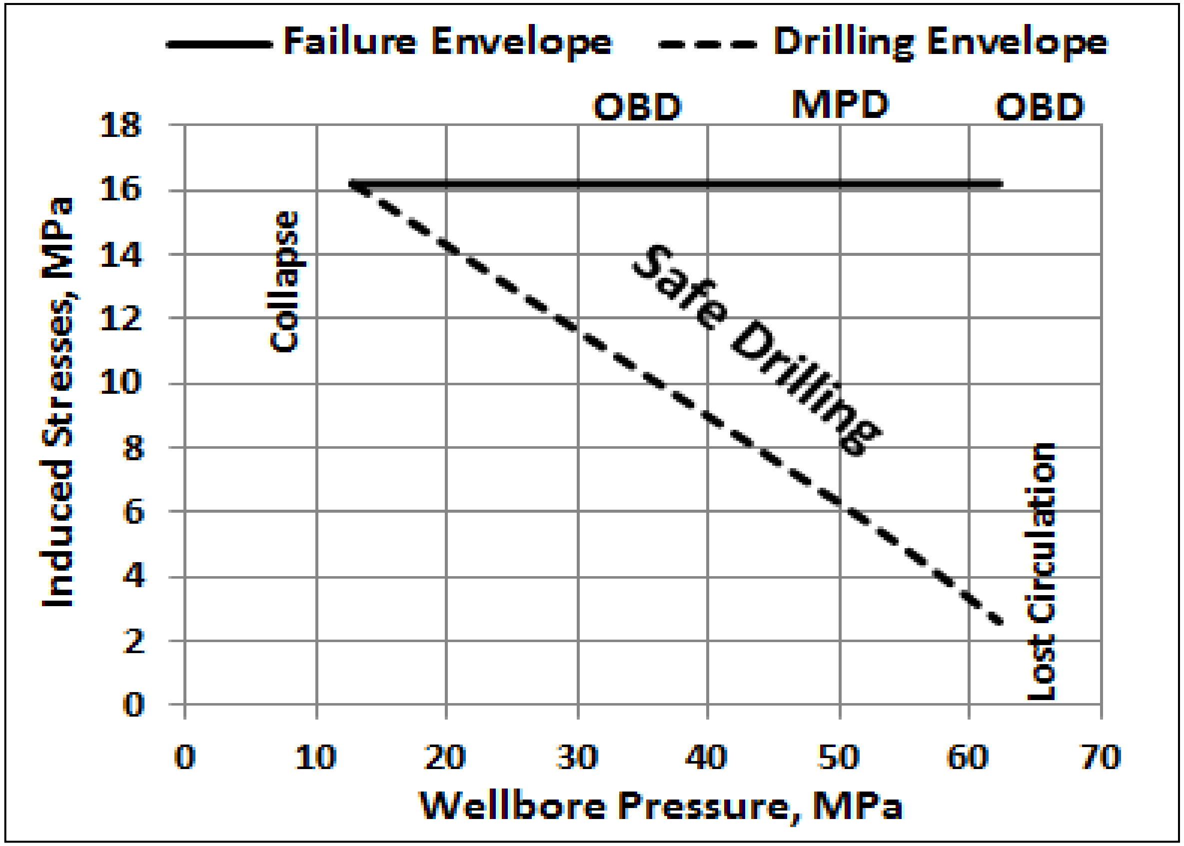


Fig. 9 Horizontal well ($//\sigma_h$) in medium strong formation (R3)

15. RESULTS AND DISCUSSION

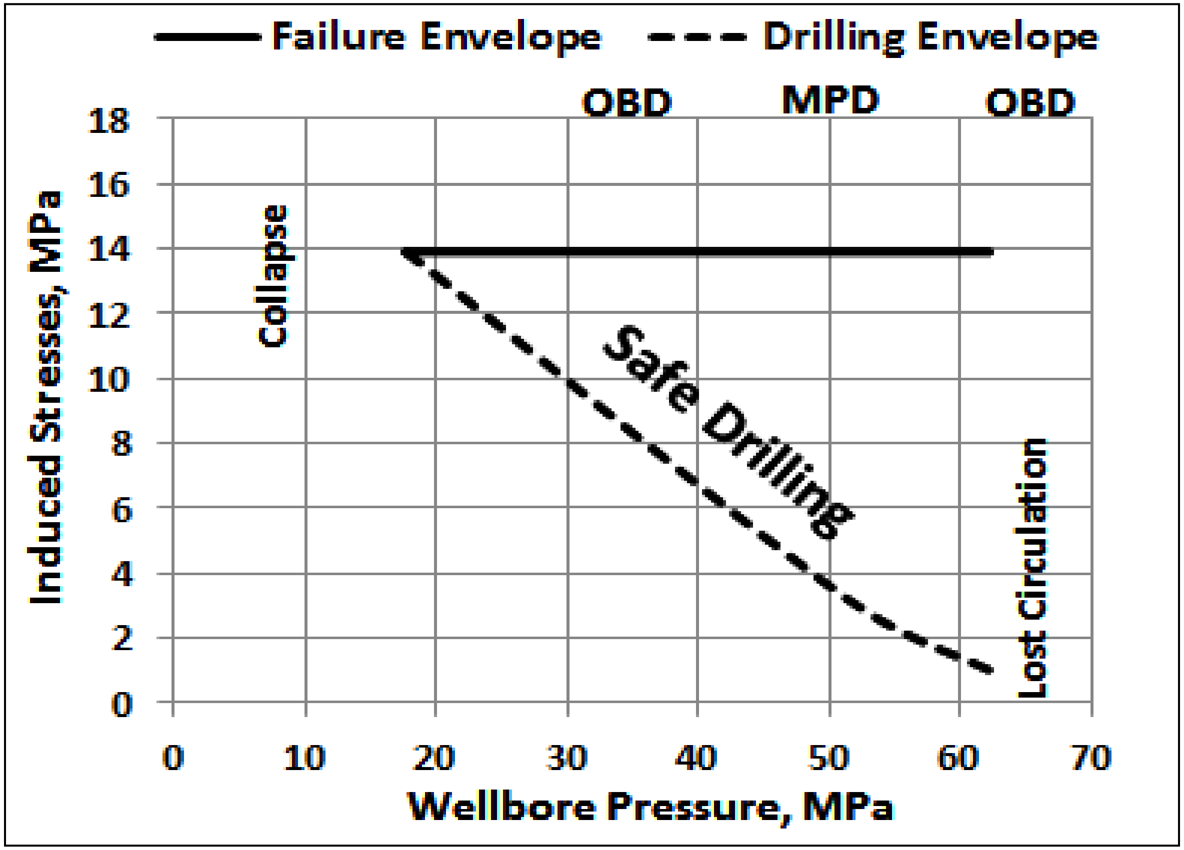


Fig. 10 Horizontal well (//σ_H) in medium strong formation (R3)

16. COMPUTED DATA
(Weak Rock – R2)

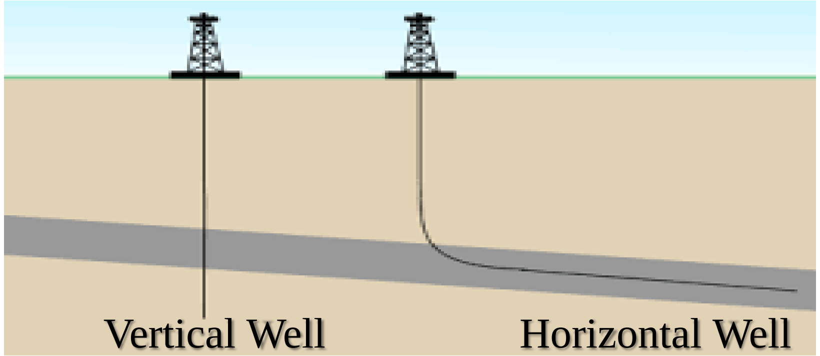


Table 4 Summary of the results of drilling vertical and horizontal hypothetical wells in R2 formation

Formation Type	Well Type	UCS, MPa	Poisson's Ratio	Friction Angle, Degree	Safe Drilling Window, MPa					
					OBD		MPD		UBD	
					$P_{wc}=(P_w-P_p)$	P_w	$P_{wc}=(P_w-P_p)$	P_w	$P_{wc}=(P_w-P_p)$	P_w
Weak (R2)	Vertical	20.6	0.23	26	+8.1	59.1	0	51	-29.2	21.8
	Horizontal// σ_h	20.6	0.23	26	+8.1	59.1	0	51	-27.5	23.5
	Horizontal// σ_H	20.6	0.23	26	+8.1	59.1	0	51	-16.6	34.4

16. COMPUTED DATA
(Very Weak Rock – R1)

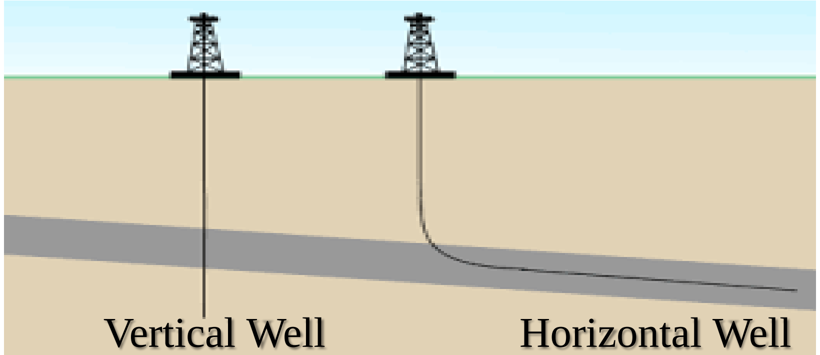


Table 3 Summary of the results of drilling vertical and horizontal hypothetical wells in R1 formation

Formation Type	Well Type	UCS, MPa	Poisson's Ratio	Friction Angle, Degree	Safe Drilling Window, MPa					
					OBD		MPD		UBD	
					$P_{wc} = (P_w - P_p)$	P_w	$P_{wc} = (P_w - P_p)$	P_w	$P_{wc} = (P_w - P_p)$	P_w
Very Weak (R1)	Vertical	6.9	0.20	21	+3.2	54.2	0	51	-19.4	31.6
	Horizontal// σ_h	6.9	0.20	21	+3.2	54.2	0	51	-17.3	33.7
	Horizontal// σ_H	6.9	0.20	21	+3.2	54.2	0	51	-1.9	49.1

17. RESULTS SUMMARY

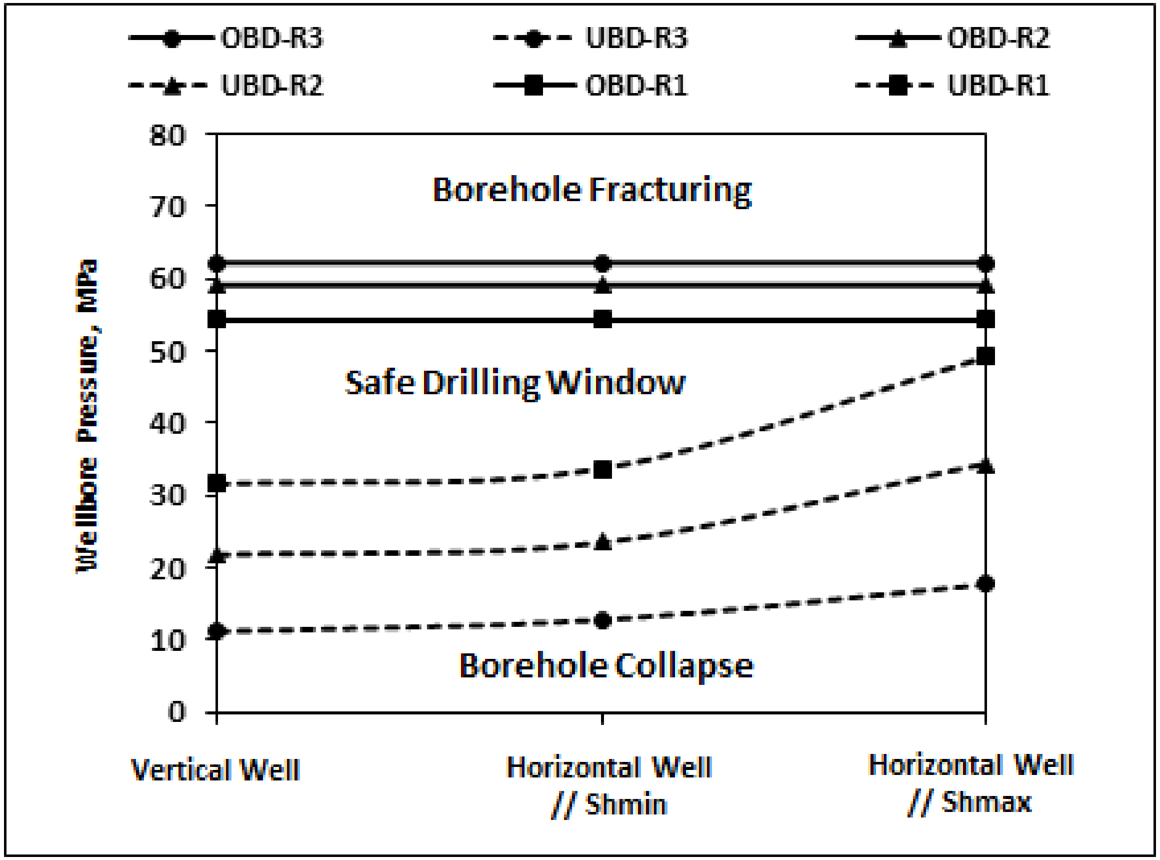


Fig. 10 Safe drilling in three different horizontal well orientations and formations strengths

18. CONCLUSIONS

Based on the analysis of the output data obtained using the mathematical model and the hypothetical formation data presented in this study, the following conclusions are attained:

- The application of UBD, MPD, or OBD is highly dependent on the formation strength, pore fluid pressure, and the in-situ principal stresses acting on the area.
- In underbalanced drilling, the window of safe wellbore pressure for vertical wells is much wider than the window of the horizontal wells under the same conditions.
- Compression (shear) and tensile failure criteria used in this work can be easily replaced if required.

18. CONCLUSIONS

- It was found that it is extremely difficult to use UBD to drill horizontal wells parallel to the maximum principle horizontal in-situ stress in the very weak rock (R1) under the studied conditions.

- In overbalanced drilling, the same window was applicable in both vertical and horizontal wells under the same studies conditions.

- In underbalanced drilling, the order of stability decrease (based on well configurations): vertical wells, horizontal wells drilled parallel to the minimum horizontal principal in-situ stress, and horizontal wells drilled parallel to the maximum horizontal principal in-situ stress accordingly.

Vielen Dank

شكرا جزيلا