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Theme

**Analysis and mitigation of wellbore instability in drilling
operations, case study: Hassi MESSAOUD field**

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Dedication

Praise be to Allah alone.

I dedicate this modest work especially to my beloved mother, my source of strength and my reason to keep moving forward, in gratitude for her endless patience, unconditional love, and countless sacrifices.

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ABSTRACT

The research investigates the causes of wellbore instability during drilling operations by using a geomechanical-based method focusing on the Hassi Messaoud Field as a case study. This study's primary aims to develop a 1D Mechanical Earth Model (MEM) that can assist to analyse and mitigate of drilling hazards like mud losses, stuck pipe, and non-productive time by integrating drilling reports, well logs, core test data, and laboratory results. Estimated in-situ stresses, pore pressures, rock mechanical properties, and safe mud weight window (MW) will be derived by utilizing a fully integrated database of previously collected data from both drilled offset wells and analysis of those wells in conjunction with either a pilot or a horizontal wellbore to predict wellbore stability and optimize overall drilling performance. The findings of this study demonstrate that advanced geomechanics modelling significantly enhances safe drilling process and wellbore design. Some limitations may arise from rock property assumptions as well as not considering all aspects of full anisotropic properties. overall, this study will prove that geo-mechanics play an important role in enhancing both the safety and effectiveness of drilling activities.

Keywords: Wellbore instability; 1D Mechanical Earth Model (MEM); Rock mechanical properties; Mud weight window; Drilling.

ملخص

تتناول هذه الدراسة تحليل عدم استقرار جدران البئر أثناء عمليات الحفر باستخدام نموذج جيوميكانيكي في حقل حاسي مسعود. الهدف الرئيسي هو تحليل وتقليل مشاكل الحفر مثل فقدان الطين، انحسار أنابيب الحفر، والوقت غير المنتج من خلال تطوير نموذج الأرض الميكانيكي أحادي البعد (1D MEM). تعتمد المنهجية على دمج بيانات الآبار مثل تقارير الحفر، المجسات، عينات الصخور، والنتائج المخبرية لتقدير الإجهادات في الموقع، ضغط المسام، وخصائص الصخور الميكانيكية، بالإضافة إلى تحديد نافذة وزن الطين الآمنة. يتم بناء النموذج باستخدام آبار مرجعية ثم تطبيقه على الآبار المائلة والأفقية للتنبؤ باستقرار جدران البئر وتحسين معايير الحفر. أظهرت النتائج فعالية النموذج الجيوميكانيكي في تقليل مخاطر الحفر وتحسين تصميم الآبار، مع وجود بعض القيود المتعلقة بالافتراضات وعدم أخذ التباين في خصائص الصخور بعين الاعتبار. بشكل عام، تؤكد الدراسة أهمية الجيوميكانيك في تحسين سلامة وكفاءة عمليات الحفر.

الكلمات المفتاحية : عدم استقرار جدران البئر؛ خصائص الصخور الميكانيكية؛ نموذج أحادي الأبعاد؛ الحفر؛ نافذة وزن الطين.

Résumé

Cette étude analyse l'instabilité des puits de forage à travers une approche géomécanique appliquée au champ de Hassi Messaoud. L'objectif principal est d'identifier et de réduire les problèmes de forage tels que les pertes de boue, le coincement des tiges et le temps non productif (NPT), en développant un modèle géomécanique de la Terre en 1D (1D MEM). La méthodologie repose sur l'intégration des données de puits, notamment les rapports de forage, les logs, les données de carottes et les essais de laboratoire, afin d'estimer les contraintes in situ, la pression des pores, les propriétés mécaniques des

roches et la fenêtre de densité de boue sécurisée. Le MEM est construit à partir des puits offset puis appliqué aux puits pilotes et horizontaux pour prédire la stabilité du puits et optimiser les paramètres de forage. Les résultats montrent l'efficacité de la modélisation géomécanique pour réduire les risques de forage et améliorer la conception des puits. Toutefois, certaines limites sont liées aux hypothèses utilisées et à l'absence de prise en compte complète de l'anisotropie des formations. Globalement, cette étude confirme l'importance de la géomécanique pour améliorer la sécurité et l'efficacité des opérations de forage.

Mots-clés : Instabilité des puits de forage ; modèle géomécanique de la Terre en 1D ; forage ; fenêtre de densité de boue.

Nomenclature

<u>Symbol</u>	<u>Meaning</u>	<u>Symbol</u>	<u>Meaning</u>
σ	Stress	R_{sh}	Resistivity of shale
F	Force	μ	Coefficient of friction
A	Area	τ	Shear stress
τ_{xy}	shear stress in x-y plane (MPa)	R	Radius
τ_{xz}	shear stress in x-z plane (MPa)	$RHOZ$	Bulk density
τ_{yz}	shear stress in y-z plane (MPa)	C	Cohesion
σ'	Effective stress	ρ_b	Bulk density
α	Biot's coefficient	g	Gravitational acceleration
p_p	Pore pressure	σ_v	Overburden (Vertical) stress
k_{dry}	Bulk modulus of the dry porous rock	QC	Quality Check
k_m	Bulk modulus of the matrix	ECD	Equivalent circulating density
ε	Strain (deformation)	E	Young modulus
l	New length	MEM	Mechanical earth model
l_0	Original length	E_{stat}	Static Young modulus
σ_r	Radial stress	$XLOT$	Extended leak off test
σ_θ	Hoop (tangential) stress	LOP	Leak off pressure
σ_z	Axial stress	FPP	fracture propagation pressure
p_w	Wellbore pressure	$ISIP$	instantaneous shut in pressure
p_m	Mud pressure	GR	Gamma ray
σ_T	Thermal stress	DST	Drill Stem Test
σ_h	Minimum horizontal stress	DTs	Shear interval transit time
σ_H	Maximum horizontal stress	DTc	compressional interval transit time
θ	Stress orientation from x-axis	ν_{sta}	Static Poisson's ratio
ν	Poisson's ratio	ν_{dyn}	Dynamic Poisson's ratio
$\sigma_{\theta min}$	Minimum tangential stress	TVD	True vertical depth
$\sigma_{\theta max}$	Maximum tangential stress	MD	Measured depth
$\sigma_{z min}$	Minimum axial stress	$DTCO$	Compressional slowness data
$\sigma_{z max}$	Maximum axial stress	psi/ft	Pound square inch per foot
σ_m	Normal stress	GPa	Giga Pascal
φ	Internal friction angle	MPa	Mega Pascal
σ_1	Maximum principal stress	g/cm^3	Gramme per cubic centimeter
σ_3	Minimum principal stress	bar/m	Bar per meter
σ_2	Intermediate principal stress	sg	Specific gravity
σ_{oct}	Octahedral normal stress	ppg	Pound per gallon
σ_{m2}	mean normal stress	m	Meters
τ_{min}	Effective minimum compressional stress	ε_{min}	Minimum deformation
τ_{max}	Maximum shear stress	ε_{max}	Maximum deformation
T_s	Tensile strength	p_{hyd}	Hydrostatic pressure
α_T	Linear thermal expansion coefficient	P	Formation pressure
ΔT	Difference of temperature	ΔT_n	Sonic transit time

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General introduction

As the demand for energy continues to rise globally, efficient and safe hydrocarbon exploration and production are growing in importance. Drilling operations are among the most critical and costly steps involved with exploration and production within the petroleum industry; however, technical challenges can negatively affect performance and profitability.

One of the most complex and costly technical challenges associated with drilling is wellbore instability. Wellbore instability can lead to many serious issues including: stuck pipe, enlarged bore holes, well collapse, lost circulation, high torque and drag, non-productive time, and in extreme cases, the total loss of the well. Due to this, understanding the reasons behind wellbore instability as well as developing methods for preventing and/or mitigating wellbore instability is now one of the top priorities in both drilling engineering and petroleum geomechanics.

The Hassi Messaoud oilfield (Hassi Messaoud, Algeria), contains one of Algeria's largest quantities of hydrocarbon resources. However, due to the field's complicated geology/geomechanics, drilling operations at Hassi Messaoud continuously encounter wellbore instability due to stress redistribution, drilling through fractured formations, and the difficulty in estimating the correct range of drilling mud weight (density). As such, a Mechanical Earth Model (MEM) must be developed, and a wellbore stability assessment conducted in order to enhance drilling efficiency and reduce operational risks.

This research analyzes the wellbore instability that exists at the Hassi Messaoud field by constructing a 1D MEM and generating wellbore stability models using logs from several previously drilled wells within the Hassi Messaoud field.

Chapter 1 covered Geomechanics and rock mechanics basics relating to wellbore stability, including what is meant by "geomechanics" in the petroleum industry, the components of in-situ stresses, effective stress and pore pressure concepts, mechanical properties of rocks (including elasticity, plasticity, stress-strain curves, rock strength), as well as examples of various rock failure mechanisms and laboratory tests used to determine rock mechanical properties.

In Chapter 2, the reader will explore wellbore stability analysis and failure mechanisms. Examples of stress distributions around the borehole, including the radial; hoop; axial stresses, methods of evaluating the stress distributions, e.g., defines the four most common rock failure criteria (Mohr-Coulomb, Mogi-Coulomb, Hoek-Brown, and Drucker-Prager), types of wellbore instability (Natural Vs. Operational causes), and methods of preventing/mitigating these instabilities during drilling operations will be discussed.

In the third chapter of our study, we have divided our research into three sections. In the first section, we will outline The methodology for developing the 1D Mechanical Earth Model (MEM) and analysing the wellbore stability of vertical well '1' includes data acquisition, estimating pore pressure, determining rock mechanical parameters, in-situ stress evaluation, and establishing a safe mud weight range as detailed in section one of the third chapter of this study.

Well '2', the pilot for developing the geomechanics model and performing a wellbore stability analysis, was drilled at an inclination angle of 22° and azimuthal angle of 40° . The geomechanical model for well '2' developed initially utilised data from the offset well '1' as no laboratory measurements or complete log data were available. The objectives of the geomechanics model were to estimate the mud weight range, evaluate shear failure and breakdown pressure, and define the mechanical behaviour of the formation.

The geomechanical model of well '2' contained the last chapter provides an overview of the effects of drilling and formation instability experienced during the horizontal drain section of well '2' on the wellbore. The horizontal drain section of well '2' was drilled at a final inclination of 88.7° and major instability issues such as differential sticking and partial mud losses were experienced due to a lack of certainty regarding the mud weight.

As a final step, a wellbore stability model was created to calibrate it with the 1D MEM. This model will evaluate and provide a final workflow for multistage fracturing operations.

CHAPTER I

GEOMECHANICS PRINCIPALES &
ROCH BEHAVIOR

INTRODUCTION

Geomechanics is a discipline that examines how rocks and soils deform or even fail under changes in stress, pressure, temperature, and other environmental conditions. In the oil industry, rocks are mainly concerned with, but the line between rocks and soils does get blurred since unconsolidated rock does act more like soil. As a branch of scientific study, geomechanics is a youth science and its application within the oil and gas industry is even younger. Nevertheless, it participates in all or almost every area of petroleum development from the search and well boring to the production and eventual abandonment on an extremely wide range of sizes starting from the micro scale interaction among PDC drill bit cutters up to gigantic models of full fields and sedimentary basins.[1]

I.1 Stress Components and Their Impact on Rock Behavior :

I.1.1 In-Situ Earth Stress

Subsurface rocks are in near-equilibrium or equilibrium stress condition prior to drilling. The natural stress in the formation is referred to as **in-situ stress**. It is primarily **compressive** owing to the overburden load of the overlying rock units. As a convention in rock mechanics, **compressive stress** is considered positive.[2]

I.1.1.1 Overburden Stress

Overburden stress refers to the stress on a specific depth geological structure due to the total weight of the overburden rocks and fluids. Most of the geological structures are created by sedimentation and compaction processes, and therefore surface and deeper layers have large variation in terms of porosity and density. For example, shallow shale structures have higher porosity and lower density compared to deeper shale structures.[2] Vertical stress, or overburden stress, can be calculated from Equation (1), provided that the density of the overlying formations is known.

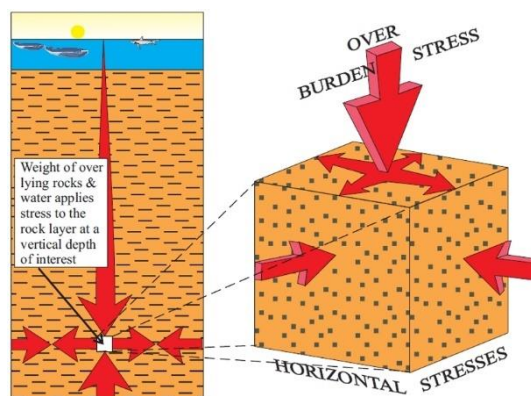


Figure I-1 Overburden stress

In the equation:

$$\sigma_v = \rho_w g z_w + \int_{z_w}^z \rho_b(z) g dz \quad \text{Eq I-1}$$

- **g**: represents the acceleration due to gravity.
- **ρ_w** : represents the density of water.
- **z_w** : represents the depth of water.
- **ρ_b** : represents the density of the formation at depth z .

I.1.1.1.1 Finding Overburden Stress

The overburden stress gradient is generally assumed to be around 1 psi/ft that reduces at shallow levels and increases with depth. Density log is an extremely precise instrument for overburden weight determination. However, if it is not present, there are other estimation devices such as Eaton's variable density curve or Wylie's time-average equation that considers sonic travel time, bulk density, and porosity.

When the rock is subjected to vertical overburden stress, it generates horizontal stress due to the constraint that is applied by the confining rock.[2]

I.1.1.2 Horizontal Stress (σ_h , σ_H)

In the majority of drilling locations, horizontal stresses are roughly equal. But while drilling close to large structures like salt domes or in tectonically active areas, these stresses may differ considerably. In these instances, they are classified into:

Minimum horizontal stress (σ_h)

Maximum horizontal stress (σ_H)

I.1.1.2.1 Minimum horizontal stress (σ_h)

The minimum horizontal stress is one of the most significant parameters used to extrapolate the fracture gradient of a formation. Drilling fluid loss into the formation—lost circulation—is normally encountered whenever the annular fluid pressure rises above the minimum stress. Basically, the minimum horizontal stress is the pressure required to extend an already-existing fracture in the wellbore wall. A typical leak-off test curve, such as *Fig I 1*, shows the relationship between leak-off pressure, formation breakdown pressure, fracture closure pressure, and the minimum horizontal stress. These relationships allow estimation of the minimum stress from direct field measurements. Additionally,

Equations (I) 1 to (I) 4 can be used to calculate minimum horizontal stress when in a condition of normal faulting stress but, when in other stress environments, adjustment needs to be done.[3]

$$\sigma_h = \frac{v}{1-v} (\sigma_v - \alpha p_p) + \alpha p_p \quad \text{Eq I-2}$$

In Equation (2), σ_h is the minimum horizontal stress, p is the pore pressure of the formation, α is Biot's coefficient, and v is Poisson's ratio. During deformation and horizontal strain, the minimum horizontal stress and strain relationship can be explained by applying Hooke's Law as illustrated in Equation (I) 3 :

$$\sigma_b = \alpha p_p + \frac{V}{1-V} (\sigma_v - \alpha p_p) + \frac{E * V}{1-v^2} \epsilon_H + \frac{E}{1-v^2} \epsilon_h \quad \text{Eq I-3}$$

Here E is the modulus of elasticity for the formation and ϵ_H , ϵ_h , the tectonic strains along the maximum and minimum horizontal directions, respectively. For transversely anisotropic formations, Equation (I) 4 can be used to determine the minimum horizontal stress.

$$\sigma_b = \alpha p_p + \frac{E_b v_v}{E_H (1-v_h)} (\sigma_v - \alpha p_p) + \frac{E_v v_v}{1-v_h^2} \epsilon_H + \frac{E_b}{1-v_h^2} \epsilon_h \quad \text{Eq I-4}$$

In Equation (I) 4 :

E_h and E_v are Young's modulus in the horizontal and vertical directions, respectively.

v_h and v_v are Poisson's ratio in the horizontal and vertical directions, respectively.[3]

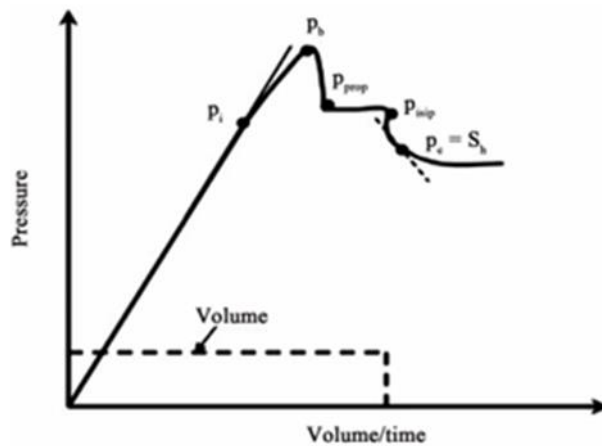


Figure I-2 Decline curve of Leak-off tests

I.1.1.2.2 Maximum horizontal stress (σ_H)

The maximum horizontal stress is among the parameters that define the best drilling operation and wellbore stability modeling. Traditionally, its estimation from wellbore breakouts has relied on the theory that the maximum tangential stress at the wellbore boundary is equivalent to the rock's uniaxial compressive strength. It is further believed that vertical, minimum, and maximum horizontal stresses have a specific relation when the formation is under stress equilibrium.[4]

The horizontal maximum stress can be calculated by means of Equation (I) 5, provided the minimum horizontal stress and vertical stress are known.

$$\sigma_H^{max} = \sigma_b + k(\sigma_v - \sigma_h) \quad \text{Eq I-5}$$

The empirical constant k is a parameter that typically ranges from 0 to 2. If the horizontal stresses are isotropic, then k will be nearly 0. If k is 0.5, the maximum horizontal stress will equal the average of the minimum horizontal stress and the vertical stress. If the formation pore pressure is known, then the upper bound of the maximum horizontal stress can be estimated from Equation (I) 6, which incorporates the generalized Hooke's law and stress equilibrium with pore pressure.[3]

$$\sigma_H^{max} = \frac{(\sigma_h - \nu p_p)}{\nu} - \sigma_v + 2 \nu p_p \quad \text{Eq I-6}$$

I.1.1.2.3 Estimating Horizontal Stress

Minimum horizontal stress (σ_h) is commonly obtained from leak-off tests. However, its maximum horizontal stress cannot be directly found by field measurements. So, its value is normally approximated using rock mechanics equations.[2]

I.1.2 Effective Stress and Pore Pressure

I.1.2.1.1 Effective Overburden Stress- σ_v :

The overburden stress that effectively stresses the rock matrix.

Effective Overburden Stress = Total Overburden Stress- Pore Pressure

$$\sigma_v = s_v - p \quad \text{Eq I-7}$$

Just as the air pressure in a car tire is what supports the weight of the car, fluid pressure in rock pores supports some of the overburden load. The remaining part of the load is what actually stresses the rock matrix and is referred to as **effective stress**[2]

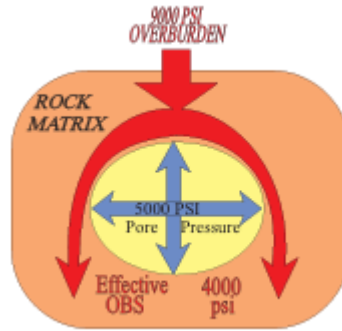


Figure I-3 Effective stress concept in rock mechanics

I.1.2.1.2 Effective Horizontal Stress (σ_h and σ_H)

Effective horizontal stresses can be calculated in the same way. Horizontal stresses are generally equal, and the effective horizontal stress is calculated by multiplying the effective overburden stress by a **lithology factor**. This factor is equal to 1 for fluids, but it is less than 1 for more rigid materials such as formation rocks.[2]

$$\sigma_h = \sigma_H = k \times \sigma_v \quad \text{Eq I-8}$$

I.1.2.2 Pore Pressure

Pore pressure is pressure induced by groundwater within the pores or spaces of rock and soil at depth. The simplest scenario is with no external influence, where the pressure equals the weight of the overlying fluid—similar to the vertical total stress equaling the combined weight of the overlying rock and fluid. This naturally occurring pressure is frequently called hydrostatic pressure. But some geological or engineering processes are able to cause the actual pore pressure to be other than the hydrostatic condition, and this departure is extremely crucial in determining the behavior of soils.

The interaction between pore pressure and soil structure creates a composite response of both. Static and dynamic loading are conveyed through the matrix of soil particles, which in turn is greatly a function of any sequestered pore water. Positive pore pressure reduces the effective normal stress (or strength) of the soil, potentially destabilizing geotechnical structures. Contractive soils, however, react to loading by developing negative pore pressure, enhancing soil stability.[5]

I.2 Mechanical properties

Mechanical properties are physical attributes that a substance displays when in contact with an external force. The major mechanical rock properties are rock strength, Poisson's ratio, and elastic

modulus. These parameters are either collected from laboratory tests on core samples or through in-situ field testing.

Mechanical Properties Include

- Elastic properties (Young's modulus, shear modulus, bulk modulus, and Poisson's ratio).
- Linear Elasticity.
- Stress and Strain.
- Inelastic properties (fracture gradient and formation strength).
- Plasticity.
- Plastic Deformation.[6]

I.2.1 Elasticity

Elasticity is a property of matter that causes it to resist deformation in shape or volume. Hooke's law describes elastic materials, stating that for the small deformations, the resulting strain is proportional to the applied stress.

I.2.1.1 Elastic properties

Under elastic deformation, a set of constants is used to relate the amount of strain caused with the stress exerted. The elastic constants are the following:

Young's modulus (E) : is a measure of applied stress to per cent extension (or reduction) of a test piece in tension or compression, the strain being defined as alteration of length in relation to the original length.

Shear modulus (μ) : is the ratio of applied shear stress to resulting plane distortion (rotation) of a plane initially perpendicular to the applied stress. It is also referred to as the modulus of rigidity.

Bulk modulus (k) : is defined as the ratio of confining pressure imposed on the sample to fractional change in sample volume due to applied hydrostatic pressure. Volume strain is calculated as change in sample volume divided by original volume. Bulk modulus is also referred to as modulus of incompressibility.

Poisson's ratio (σ_p) : is the ratio of lateral strain (which is perpendicular to the direction of applied stress) to longitudinal strain (which is parallel to the direction of applied stress).

It is an indication of the way a material deforms in directions perpendicular to the direction of applied force, and is critical in understanding the overall deformation behavior of the material under stress.

I.2.2 Stress and strain

When a stress (σ) is applied to a material such as rock, the material will either change in volume, size, or shape. This change or deformation is what is called strain (ϵ).

Stresses can be axial such as direction tension or simple compression, shear (tangential), or all-sided such as hydrostatic compression.

The terms stress and pressure are sometimes used interchangeably, yet stress normally implies directional or shearing stress while pressure (P) implies hydrostatic compress.

Under minor stresses, strain is elastic—one can "turn it around" upon withdrawal of stress and has linear proportion with applied stress.

At huge stresses or for other conditions, strain might be inelastic or permanent.[6]

I.2.3 Plasticity

Plasticity is the ability of some solids to change shape, or deform permanently, or to flow under stresses of intermediate magnitude—greater than those producing elastic (transient) deformation but lower than those leading to material failure or rupture. Plasticity allows a solid to deform permanently under the action of external forces without breaking.

Such deformation occurs in most metal-working operations such as rolling, pressing, and forging, and also in geological processes such as folding of rocks and rock flow within the Earth under extremely high pressures and high temperatures.[6]

I.3 Rock Strength and Rock failure

Strength is a quantitative measure of the capacity of a material to withstand an applied external load. In rock mechanics, it is the force divided by area which must be applied to cause rupture in a rock mass under given environmental conditions. Rock strength is a function of several factors such as mineralogical composition, shape of the grains, texture, crystallinity, stratification, lamination, and heat or pressure alteration. Secondary processes such as cementation and weathering also significantly impact rock strength.[7]

Core samples, extracted from in-situ environments, are normally put through a test in compression within a laboratory environment. Being a step closer to more simulative subsurface testing, they are also confining pressure-tested (σ_c). Rock will deform with variation in volume, shape (deformation), or both as it reacts to imposed stress. A change of state is referred to as strain.

When subjected to compressive (+) or tensile (–) stress, rocks can go through three stages of strain. During the elastic deformation stage, the stressed rock deforms but returns to its original shape upon removal of the stress. The strain is proportional to the stress in this stage as provided by Hooke's Law.

When applied stress equals the elastic limit, the rock begins exhibiting plastic deformation. During plastic deformation, the rock recovers partially to its original shape when stress is removed. When stress is increased further, fractures develop and the rock fails (ultimate failure).

Rocks can fail in a brittle manner, typically at low confining stress, or in a ductile manner at greater confining stress.[2]

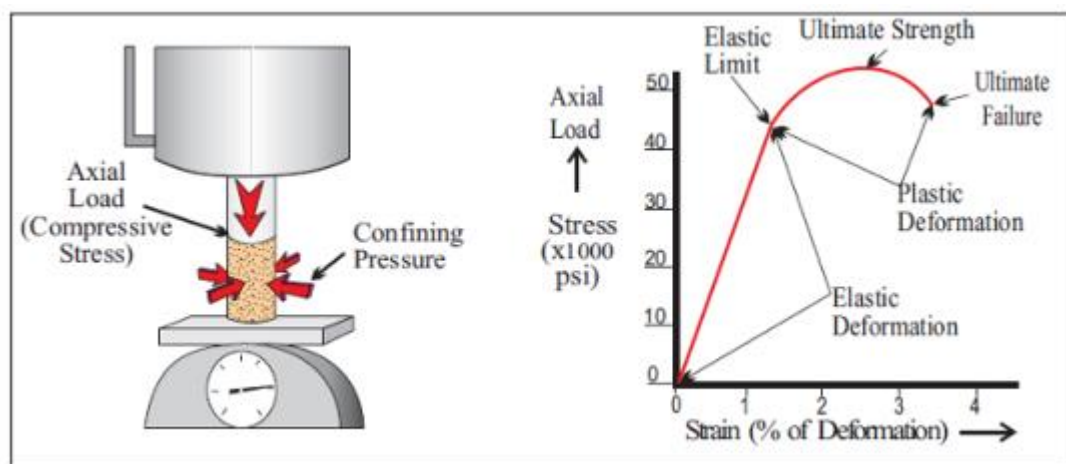


Figure I-4 Typical stress-strain behavior of a material

- Classification of strength: based on type of loading and the stresses, the overall strength can be rated as:

1. Compressive Strength
2. Tensile Strength
3. Shear Strength.[6]

I.3.1 Compressive Strength

The compressive strength of a material is a measure of its ability to resist uniaxial compressive loads without yielding or fracture. Most widely used measure of compressive strength is the Uniaxial compressive strength or unconfined compressive strength. It is one of the most important properties used in design, analysis and modeling.

Direct Methods:

- Uni axial Compression Test

- Tri axial Compression Test

Indirect Method:

- Point Load Test
- Schmidt hammer Test [8]

I.3.2 Shear Strength and Shear Failure

I.3.2.1 Shear Strength

It mostly deals with the shear strength and shear behavior of the shearing and weakness planes of the rock which hold together a rock specimen. o It is a vital geomechanics measure, used for design.[6]

I.3.2.2 Shear Failure

Shear failure is when the shear stress along a specific plane in the sample is adequate. Ultimately, a fault zone forms along the failure plane, and the two sides of the plane move past each other in a friction process. It is a known fact that the frictional force opposing the relative motion between two contacting bodies depends on the force that presses the bodies against one another. Therefore, it would be reasonable to anticipate that the critical shear stress (τ_{max}) at which shear failure occurs is a function of the normal stress (σ) on the failure plane.[9]

I.3.3 Tensile Strength and Tensile failure

I.3.3.1 Tensile Strength

Tensile strength of a material is defined as the maximum tensile stress which a material can develop o In nature rock mass is rarely subjected to direct tension, but it is subjected to tensile stresses o Rocks are weak in tension.[6]

I.3.3.2 Tensile failure

Tensile failure occurs when the rock undergoes stresses that aim to stretch the rock apart, or tensile stresses. Since rocks have generally very low tensile strength compared to their compressive strength, they will tend to fracture under tension. Tensile failure is especially crucial in drilling where pressure losses occur suddenly and have a tendency to induce tensile stresses around the wellbore.[2]

I.3.4 Rock failure tests

I.3.4.1 Unconfined Compression (UC) Test

The prime purpose of the Unconfined Compression (UC) Test is to determine the unconfined compressive strength (q_u) of the sample of the soil, which would be used in the computation for the unconsolidated undrained shear strength of the clay when unconfined.

According to ASTM practice, the unconfined compressive strength is the compressive stress at which an unconfined test cylinder of soil fails in a simple compression test. In this test, the unconfined compressive strength is taken as either:

- Maximum load obtained per unit area.
- Load per unit area at 15% axial strain,
- Whichever is obtained first in the test.

In this test, a cylindrical soil sample is loaded under compressive stress (σ_1) axially without lateral confinement. This means that the minor principal stresses (σ_2 and σ_3), i.e., the confining pressure, are zero.[10]

ASTM: American Society for Testing and Materials.



Figure I-5 unconfined compressive strength test

I.3.4.2 The Brazilian tensile test

The Brazilian tensile test, or splitting test, is a widely used indirect test of the tensile strength of rocks and other hard, brittle materials by applying diametral compression on a circular disc. The test is favored in rock engineering due to the ease of specimen preparation, easy performance, and availability of uniaxial compression test machines.

The Brazilian test, created in 1943, has principally been applied to homogeneous rocks. Relatively little has been said regarding the application of it to anisotropic rocks, and the interpretation of tensile strength results becomes a challenge in such a situation. Structural elements such as bedding or foliated textures (transverse isotropy) in experiments of how they influence test results are relatively rare, especially when varying the loading axis orientation against planes of weakness.

With symmetrically distributed load across two evenly balanced peripheral arcs, nearly biaxial compression and horizontal tension are achieved along the diameters line crossing through the middle of the sample. This commonly leads to tension fracture along the diameter that's under load, cutting the disc (or the cylinder) in two.[11]



Figure I-6 Brazilian tensile strength test

CHAPTER II

STRESS-INDUCED WELLBORE
INSTABILITY & FAILURE CRITERIA

Introduction

A decrease in wellbore stability (WBS) analysis can lead to a number of problems, including collapse, stuck pipes, blowouts, breakouts, kicks, mud losses, and wellbore washouts. Wellbore instability can also result in borehole abandonment before it reaches its target point, which raises drilling expenses and time. On average, these problems cost about 10% of the total drilling time. Additionally, wellbore instability is a very complex issue, and a number of elements are thought to be important, including drilling mud and pore fluid chemistry, mud density, duration, temperature, pore pressure (Pp), wellbore trajectory, rock mechanical characteristics, and far-field primary stresses.[12]

II.1 Influence of stresses on wellbore integrity

Making a round hole and using drilling and completion fluids on a seemingly stable formation is thought to cause a set of events that mainly lead to wellbore instability and casing failure.[13]

Relying on no nearby seismic events, rock formation is normally in a balanced (static) stress condition with little or no movement before any excavation. In situ stresses refer to the three main stresses present in such a static stress condition. Excavation disturbs the static stress condition, which thus causes rock formation instability.

The altered in situ stress condition would consequently create a distinct set of strains in the excavating region(**Fig II.1**)shows a schematic of in situ stresses present in the formation around a wellbore. The initial stage of conducting formation stability analysis is to find this stress condition. We now convert the in situ stress plate of (**Fig II.2**) to those shown in Figure II-1 to investigate further stress condition surrounding the wellbore. A shows rock formation when originally there is no hole in it. All sides of this plate are loaded, giving it a consistent stress condition.

Drilling a hole into it will affect the stress state since the circular hole creates a stress concentration reaching many wellbore diameters distant from the hole. The altered geometrical condition will now change the stress state surrounding the hole, as seen in (B)

In general, drilling operations generate a redistribution of tensions around the well. The redistributed stresses, referred to as induced stresses, include Hoop stress acting around the circumference of the wellbore (tangential); radial stress acting along the radius ;axial acting parallel to the well path. These stresses are designated by (σ_θ , σ_r , σ_z).The wellbore wall serves as a primary stress plane and is significantly influenced by the generated stresses resulting from drilling operations. This

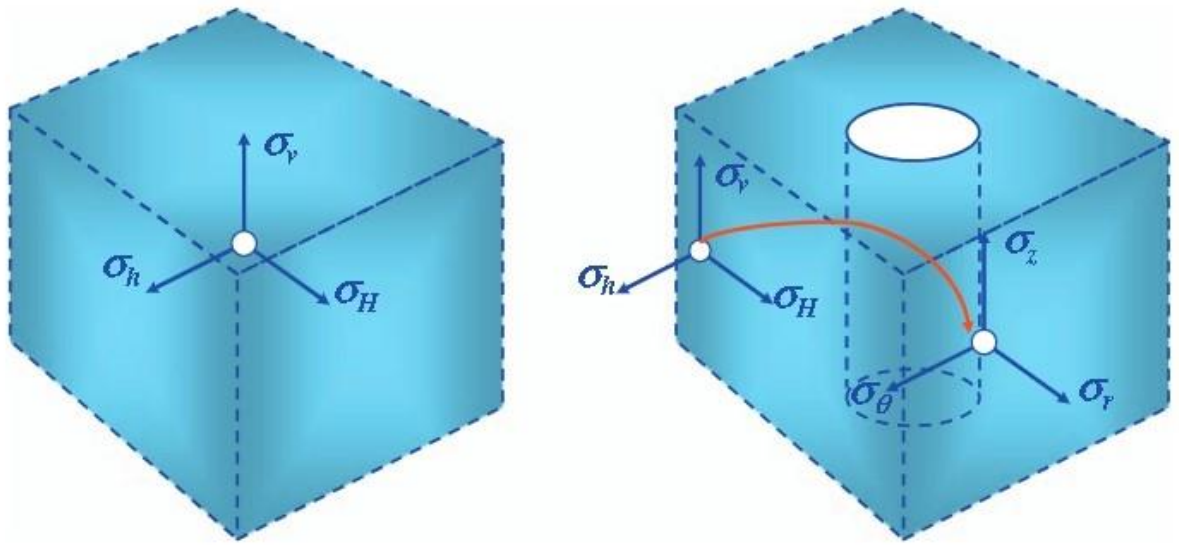


Figure II-1 (A) Rock formation with uniform stress state and (B) rock formation with a drilled hole where the stress state will not remain unchanged.

will lead to several incidents, with wellbore instability and sand production being but two instances among many.[5]

II.1.1 Hoop stress (σ_θ)

Hoop stress is the stress that acts tangentially around the circumference of the borehole wall. it depends on wellbore pressure, insitu stress magnitude and orientation, pore pressure, hole inclination and direction.

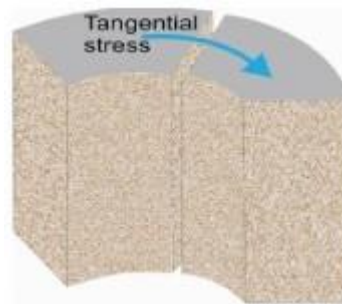


Figure II-2 Hoop stress

Hoop stress for a vertical wellbore with equal horizontal loads is dependent on the mud weight and the level of the horizontal strains; it is uniformly distributed throughout the wellbore.

Based on Kirsch equations we can provide closed-form solutions to determine the stresses around a circular, excavated area.

$$\sigma_{\theta} = \sigma_h + \sigma_H - p_p - p_m - 2(\sigma_H - \sigma_h) \cos 2\theta \quad \text{Eq II-1}$$

II.1.2 Axial stress(σ_z)

Axial stress is a kind of stress that is directed along the path of the wellbore and might be spread in an uneven manner around the wellbore. The components that determine axial stress are the magnitude and orientation of the stress, the pore pressure, and the inclination and direction of the hole.

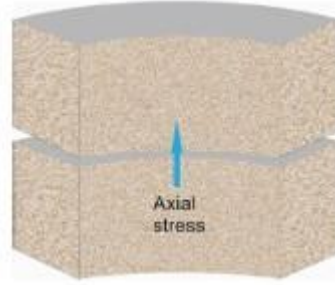


Figure II-3 axial stress

The weight of the mud does not have a direct impact on axial tension. For a vertical well with equal horizontal stress ($\sigma_H = \sigma_h$), axial and vertical stress are the same. Axial stress in a deviated well is the resolution of the overburden and horizontal stresses

So basically, the Kirsch equations let us determine how the axial tension varies across a wellbore. Drilling into the rock causes inconsistent load distribution; these equations illustrate how it redistributes across that circular hole.

$$\sigma_z = \sigma_v - p_p - 2\nu(\sigma_H - \sigma_h) \cos 2\theta \quad \text{EqII-2}$$

Where : σ_v is the vertical stress, p_p pore pressure, σ_H is the maximum in-situ stress and σ_h the minimum horizontal in-situ stress , θ angle from the direction of the maximum horizontal stress σ_H

II.1.3 Radial stress (σ_r)

Radial stress, which is along the radius of the wellbore, is the wellbore pressure minus the pore pressure.

$$\sigma_r = p_w - p_p \quad \text{Eq II-3}$$

Because both pore and wellbore pressures are generated from fluid pressure that acts uniformly in all directions, this pressure difference is acting along the radius of the hole perpendicular to the wellbore wall.



Figure II-4 radial stress

This radial stress may impose an important effect on the stability and integrity of the well. Wellbore instability may cause issues such as wellbore collapse or formation damage when the radial stress exceeds the strength of the rock formation. The success of drilling operations and the wellbore integrity depends on thus controlling and understanding this radial stress.

II.2 Wellbore Failure Criteria

Rock failure happens when a piece of rock is under sufficient stress. The failure process alters this kind of rock. Under this state, the rock cannot support weights. In wellbore rock mechanics, rock failure is extremely crucial since it causes several issues.[14]

Usually, the failure analysis of materials is done by contrasting the internal stresses with the material strength. Should the stresses not surpass the rock strength(whether tensile, compressive, or shear),we then regard the material to stay intact.[5] Several well-known failure criteria are commonly used in engineering analysis .these include Mohr-Coulomb

criterion, Hoek-Brown criterion, Drucker–Prager and Mogi–Coulomb criterion, etc.

II.2.1 Mohr–Coulomb Failure Criterion

The Mohr-Coulomb (M-C) yield function is among the most often used and known. Originally based on many experimental studies of Coulomb on the shearing of rocks and soils along a failure plane, this yield function is particularly designed for frictional material such rock and soil.

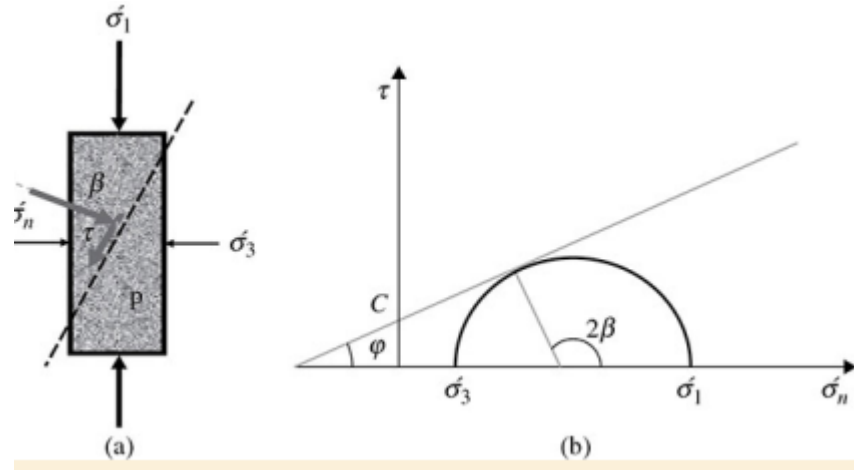


Figure II-5 M-C failure criterion: (A) failure plane inside the rock sample and (B) M-C plot in τ - σ'_n space along with the Mohr's circle

experimental studies of Coulomb (1773) on the shearing of rocks and soils along a failure plane. It may be seen as the generalization of the Tresca criterion including the influence of average stress. This failure function suggests that a geomaterial's strength originates from two primary sources.[15] One source is the frictional resistance on the failure plane, or a function of normal stress on the plane. The other source relates to the internal cohesion of the material, which indicates the resistance of a geomaterial to shear in the absence of normal stress. From a mathematical standpoint, this failure function may be expressed as follows :

$$|\tau| = c + \mu \sigma'_n \quad \text{Eq II-4}$$

where τ and σ'_n are the shear stress and effective normal stress on the failure plane (Fig. 4a). The parameter c stands for the rock/soil cohesion and μ is the internal friction coefficient on the failure plane inside the rock. In $\tau - \sigma'_n$ plane (Fig. 4.10b), Eq. (4.3.24) is a straight line with a slope of μ and an intercept of c . The angle between the line and the horizontal axis, φ , is called internal friction angle, which is related to the angle β , the angle between normal to the failure plane and direction of maximum principal stress. The relation between β and φ is given by:

$$\beta = \frac{\pi}{4} + \frac{\varphi}{2} \quad \text{Eq II-5}$$

The principal stresses at failure (which contact the failure line) are represented by the Mohr's circle shown in this figure. The rock or soil will fail as soon as the Mohr's circle reaches the failure line, so any stress combinations that extend the Mohr's circle above the failure line are not physically available. The M-C failure criterion can be expressed in terms of the principal stresses as follows:

$$f(\sigma_{ij}, p, k) = \sigma'_1(1 - \sin \varphi) - \sigma'_3(1 + \sin \varphi) - k = 0 \quad \text{Eq II-6}$$

where $k = 2c \cos \varphi$. According to this equation, the stress at failure increases linearly with confining pressure.

II.2.2 Mogi-Coulomb Failure Criterion

In order to solve the problem that comes up when studying wellbore stability, many experts have come up with a lot of true-triaxial failure criteria. Even though these true-triaxial failure criteria were much better at predicting how the π_2 would affect things, most of them needed more specific strength factors. In 2005, Al-Ajmi and Zimmerman came up with the MG–C criterion and showed that it can fairly accurately model true-triaxial failure data from a number of different rocks. Additionally, the MG–C criterion only needs two strength parameters to be used: the cohesive strength and the friction angle. These parameters are easy to find in the field. So, the MG–C criterion was also used to find the shear failure.[16] The MG–C standard can be written as

$$\tau = a + b\sigma_{m,2} \quad \text{Eq II-7}$$

Where,

$$\begin{cases} \tau_{oct} = \frac{1}{3}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{\frac{1}{2}} \\ \sigma_{m,2} = \frac{1}{2}(\sigma_1 + \sigma_3) \end{cases} \quad \text{Eq II-8}$$

Where, a is the intersection of the line on τ_{oct} -axis, and b is the inclination of the line. The strength parameters a and b are related to the friction angle and the cohesive strength of the rock, and can be calculated by following equations

$$\begin{cases} a = \frac{2\sqrt{2}}{3}c_0 \cos \varphi \\ b = \frac{2\sqrt{2}}{3} \sin \varphi \end{cases} \quad \text{Eq II-9}$$

On this basis, we also can define a function f_{MG-C} to determine the shear failure, And wellbore shear failure will occur when $f_{MG-C} \leq 0$.

$$f_{MG-C} = a + \frac{1}{2}(\sigma_1 + \sigma_3)b - \frac{1}{3}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{\frac{1}{2}} = 0 \quad \text{Eq II-10}$$

II.3 Wellbore instability

A well is considered unstable if there is so much failed material produced by excess breakout development around the wellbore that mud circulation is unable to move the whole volume of cuttings and failed material out of the hole. In actuality, the velocity of drilling mud in the annulus between the outside of the bottom hole assembly and the wall of the hole reduces as a wellbore grows larger as a result of severe wall failure. Consequently, the mud's capacity to remove cuttings and debris from the well is diminished. Cuttings and failed rock may stick to the bottom hole assembly due to rock the decreased cleaning ability brought on by mud circulation. Because it appears as though the wellbore has collapsed in on the bottom hole assembly, this phenomenon is frequently referred to as wellbore collapse. The collapse pressure is sometimes used to describe the weight of mud required to stabilize the wellbore wall and stop this from happening.[17]

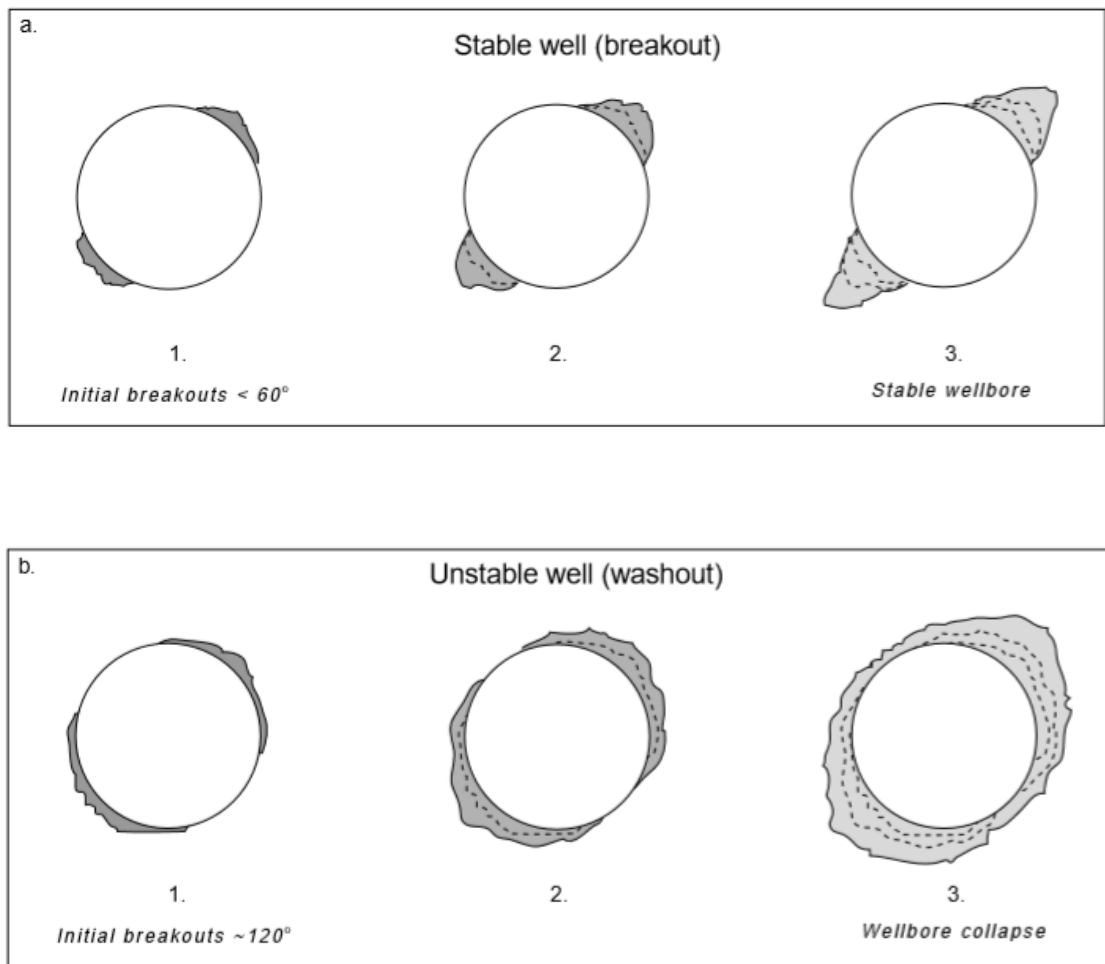


Figure II-6 (a) Schematic representation of breakout growth when the initial breakout size is relatively small ($<60^\circ$) and (b) when it is relatively large ($\sim 120^\circ$).[22]

Wellbore instability scenarios are categorized as either a tensile or shear failure in the majority of the literature that is currently available. Nonetheless, there are three primary failure modes that affect rocks on Earth: compactive, tensile, and shear failure.[2]

Wellbore instability comes in a variety of forms, including;

- Wellbore collapse
- Tight holes
- Hole enlargement
- Wellbore fracture
- Shale instability

II.3.1 Wellbore collapse

Hole collapse occurs when the formation next to the borehole fails mechanically,[9] it is linked to low borehole pressures, usually as a result of an extreme reduction in mud weight.[5]

Mud pressure, pore pressure, time, in-situ stresses, the elastic and hydraulic characteristics of the formation, and wellbore geometry all affect the effective collapse stress.

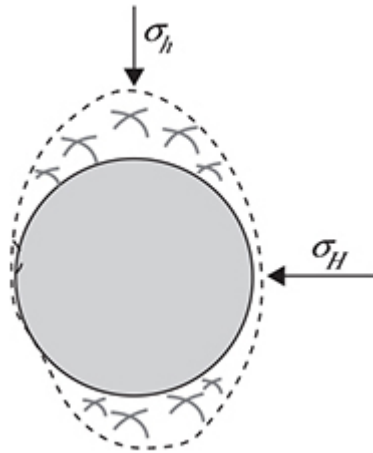


Figure II-7 Schematic of wellbore collapse[18]

II.3.2 Tight holes

Dog leg severity, inward creep of the wellbore, shale swelling, and low borehole pressure are some of the reasons why drilling tight holes can result in a severe drop in wellbore diameter in a section or sections of the wellbore. Stuck pipes, trouble landing casings, trouble cleaning holes, and trouble cementing can all result from this problem. By raising the mud weight, the tight hole circumstances can be reduced or even removed .[18]

II.3.3 Hole enlargement

A wellbore instability condition known as "hole enlargement," or "washouts" in some literature, occurs when the wellbore diameter unnecessarily increases beyond that of the bit that drilled the section. Among other things, this can be brought on by hydraulic erosion (which is brought on by high mudflow close to the drill bit), or softening of the formation owing to mechanical failure, mechanical abrasion from drill string vibration and inherently sloughing shale. Poor logging results, trouble placing cement behind casing, and hole cleaning are all examples of the negative effects.[18]

II.3.4 Wellbore fracture

Natural fractures in the formation might make the well's stability study more difficult since they will change the pore pressure and stress distribution surrounding the borehole, which will change the reservoir rock's hydraulic and mechanical characteristics. Due to the differential pressure between the drilling fluid and the rock the fluid will penetrate into the formation. The drilling fluid will enter the natural fissures considerably more quickly than the rock matrix due to their high permeability, which will raise the effective stresses. Wellbore failure generally happens along the maximum horizontal principal stress in heavily fractured rocks. Furthermore, one of the primary causes of borehole instability in fractured rocks is the drilling fluid's entry into the joint plane, which lowers its resistance and causes the borehole to collapse or shatter.[19] This may be followed by a loss of circulation, which, depending on its severity, may result in a significant drop in the wellbore's drilling fluid level and, as a result, its hydrostatic pressure, raising the possibility of a blowout.[18]

II.3.5 Shale instability

While each of the above type of wellbore instability can be classed as either shear or tensile failure, shale instability can occur in some situations as a shear failure, when triggered by insufficient borehole pressure.[18] mechanical features of shale-drilling fluid interactions play a crucial influence in wellbore instability of shales . To prevent any stability issues, a various shale inhibitors suppress and stabilize shale. Drilling issues connected to reactive shale can be effectively controlled by combining a number of inhibitory strategies.[10]

II.4 Causes of wellbore instability

II.4.1 Uncontrollable (natural) factors

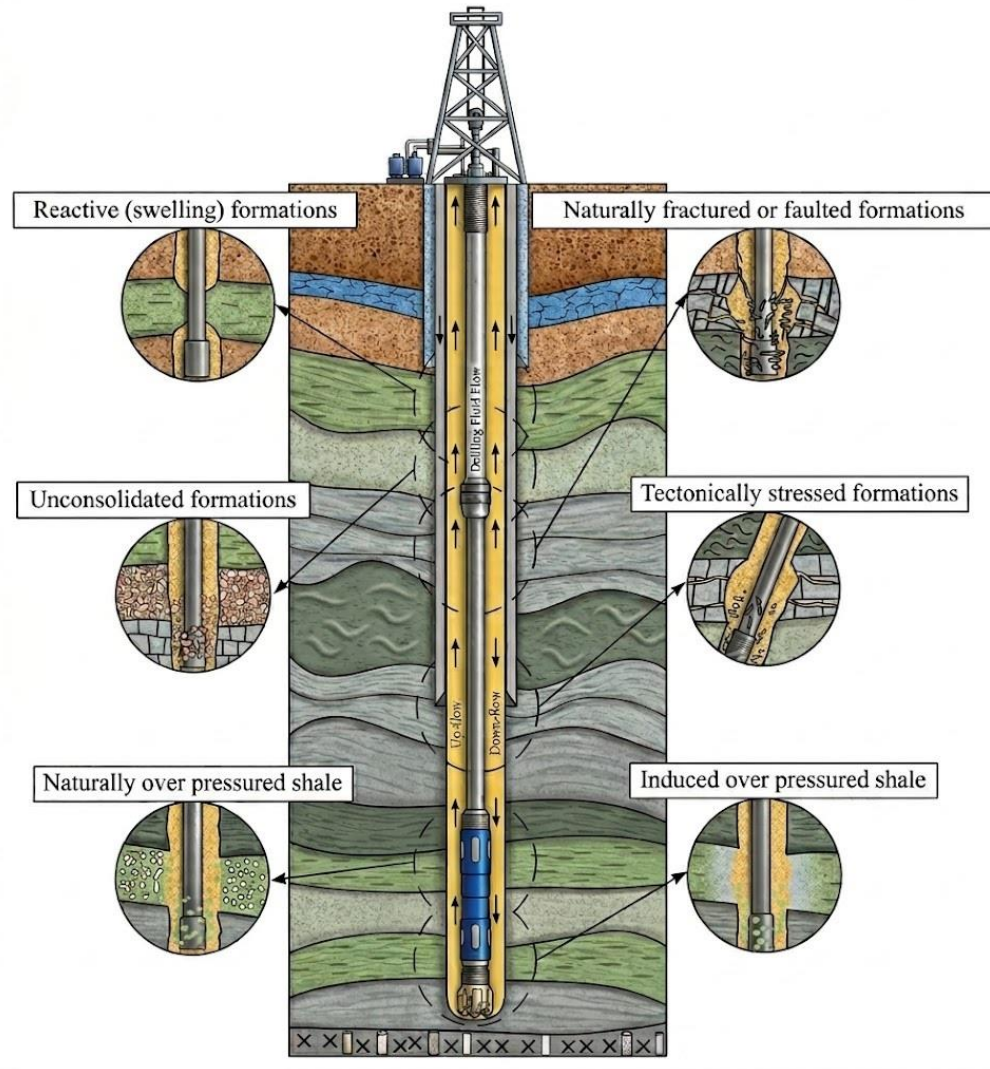


Figure II-8 situations that can cause wellbore instability [26]

II.4.1.1 Tectonically Stressed Formations

In regions where the earth's crust is moving and compressing or stretching rock, tectonic stresses accumulate. The pressure of the shifting tectonic plates is causing the rock in certain places to buckle. The rock surrounding the wellbore will collapse into the wellbore when a hole is drilled in an area with significant tectonic stresses, creating splintery cavings similar to those created by over-pressured shale..[20]

II.4.1.2 High in-situ stresses

At a certain depth in the Earth, formations are exposed to pore pressure, vertical compressive stresses, and horizontal compressive stresses that are typically anisotropic. The load that was previously supported by the removed rock must now be supported by the surrounding rock when a hole is drilled. In a rock that exhibits linear elastic behavior this results in a concentration of stress close to the well, this concentration of stress may cause the borehole to fail if the rock is weak enough [9]. Wellbore instability may result from abnormally high in-situ stresses, such as those seen in the inner limbs of a fold, next to faults, or around salt domes. Particularly rigid rocks, such as quartzose sandstones or conglomerates, can also have concentrations of stress. Such in situ stresses are difficult to be measured.[20]

II.4.1.3 Naturally over-pressured shale collapse

Borehole stability difficulties are often encountered in over-pressured shale. In these shale formations, the natural pore pressure of the formation is higher than the standard hydrostatic pressure of a column of pure water. The application of insufficient mud weight in some areas of the wellbore can lead to wellbore collapse.[18] Shale permeability is low enough that a thick shale formation may not be able to release fluid at the same pace as it is compacted. Sands which are contained within such shale deposits are likewise liable to get over-pressured. It goes without saying that rapid sedimentation is another potential cause of overpressures. Over geologic time, abnormal pressures caused by disequilibrium compaction often decrease.[9]

II.4.1.4 Mobile formations

The force of compression applied by the overlaying rock mass causes mobile formations to flow or squeeze into the wellbore under inadequate hydrostatic pressure; this deformation results in a reduction in hole diameter, makes it difficult to land casing and logging tools, and causes issues with hole cleaning. To help stabilize these formations, it is necessary to maintain adequate drilling fluid weight while drilling through such intervals.[18]

II.4.1.5

II.4.2 Controllable factors

II.4.2.1 Bottom hole pressure (mud density)

Mud weight, bottom hole pressure, or equivalent circulating density (ECD) is generally the most significant primary wellbore stability indicator. One of these parameters is generally most dominant in controlling whether an open wellbore would be stable, based on application. The stabilizing pressure of the static or dynamic fluid pressure, while performing operations like drilling, stimulating, working over,

or producing a well, plays an important role in the computation of the stress concentration near the wellbore region.[21]

As rock failure is a function of effective stress, wellbore stability is highly dependent on the degree and rate at which fluid pressure invades the wellbore wall. This does not imply that either higher bottom hole pressures or higher mud densities are always beneficial in preventing instability. In certain instances, bottom hole pressure increase can be unhealthy for wellbore stability and negate other significant parameters, such as Formation damage, Differential sticking risk, Mud properties and Hydraulics, This is especially so when there is no efficient filter cake, e.g., in fractured formations.[20]

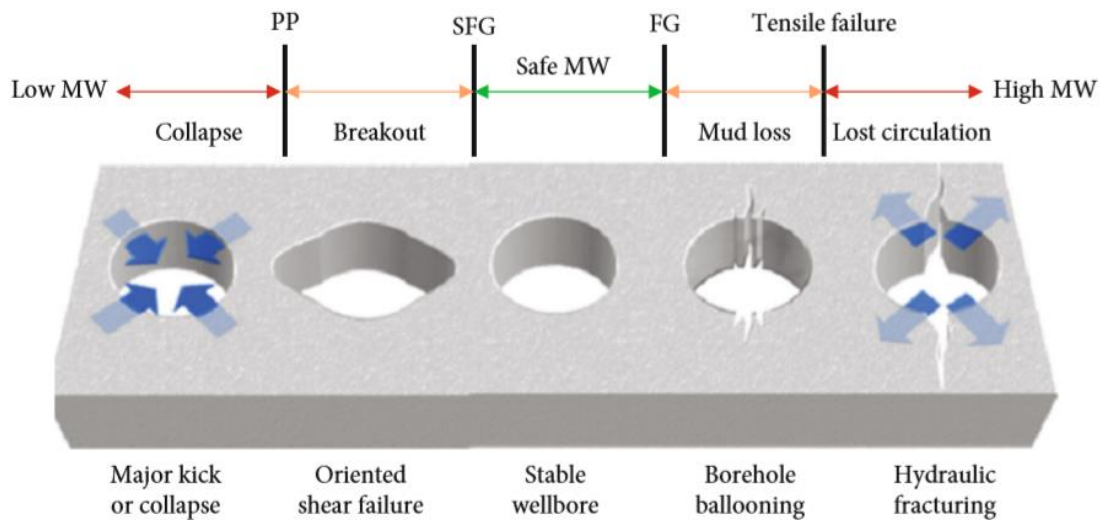


Figure II-9 Relationship between mud weight and wellbore failures, modified from Well Inclination and Azimuth[33]

II.4.2.2 Well Inclination and Azimuth

The relative azimuth and inclination of the well to the principal in-situ loads can greatly impact the potential for wellbore fracture breakdown or collapse. This is especially critical in attempting to predict the fracture breakdown pressure, particularly in tectonically stressed regions with high stress anisotropy. By knowing the direction of the well in relation to the principal stress directions, more precise predictions can be made on the stability of the wellbore and the likelihood of failure during production or drilling.[20]

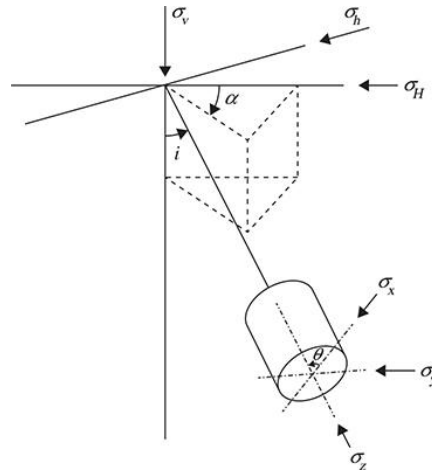


Figure II-10 Schematic diagram for an inclined wellbore subjected to in-situ stresses [18]

II.4.2.3 Transient Pressures in the Wellbore

Swab and surge pressures while drilling cause transient stresses that destabilize the wellbore. They are created by the piston-like movement of the drill string in the hole filled with mud, particularly at high tripping speeds and with viscous muds. Their effect encompasses:

- Instant failure on low-pressure cycles when stress exceeds rock strength.
- Delayed failure caused by pore pressure increase near the borehole wall after cyclic loading. Fatigue failure due to cyclic stress, based on amplitude and cycles.

Swabbing will induce tensile spalling in weak or pre-fractured rock, and surge will rapidly build up pore pressure and result in collapse. Filter cake efficiency and capillary threshold pressures sustain stable permeable formations.[9, 20]

II.4.2.4 Mud/Rock Interaction

In water-based mud (WBMs) drilling, shales are less stable than sands or carbonates because chemical interactions are capable of actually decreasing the shale strength by an enormous amount. There are two general mechanisms of such instability:

Osmotic Diffusion:

Water from low-salinity mud diffuses into the formation due to an osmotic pressure gradient at the mud–rock interface. If the mud’s water phase salinity is lower than the pore fluid salinity in the formation, water is drawn into the shale. This results in:

- Increased pore pressure
- Shale swelling and weakening

A common solution is to increase the salinity of the mud water phase, which can reduce the osmotic gradient and stabilize the formation.

Chemical Diffusion:

Specific ions migrate from high concentration (in the mud) to low concentration (in the formation), altering the clay structure via cation exchange. This weakens the shale over time.

Enhancing membrane efficiency can mitigate chemical diffusion. A membrane with higher efficiency restricts ion exchange more effectively.

II.4.2.5 Drill string vibration

Drillstring vibration is an important factor contributing to wellbore instability, and its impact is dependent on vibration mode and magnitude. The main vibration sources are interactions between the formation and bit and the drillstring to wellbore contact. Vibration can be in various modes: axial vibration, which is along the length of the drillstring; torsional vibration, which is as rotational motion about the drillstring axis; and lateral vibration, which results in side-to-side motion. The most damaging is the lateral vibration, which is one of the main wellbore enlargement and instability causes.

Vibration has several negative consequences on drilling operations. It can cause pipe failure and fatigue, such as twist-offs or washouts. It also reduces the life of the drill bit and ruins well direction control, causing the well to deviate from the intended path. Another serious effect is borehole enlargement, which will undermine the wellbore stability and destabilize it. Furthermore, vibration lowers drilling efficiency, which leads to increased operational expense, and may result in high torque at drillstring connections, leading to additional issues.

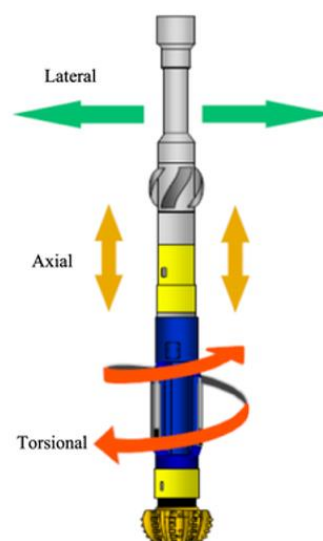


Figure II-11 Vibration form of drill string [35]

CHAPTER III

1D MECHANICAL EARTH MODELING
(CASE STUDY)

III.1 1D Mechanical Earth Model

A mechanical earth model (MEM) is a collection of data, including measurements and models, that represent the mechanical properties of rocks and fractures, as well as the stresses, pressures, and temperatures that affect them at depth. Engineers and geoscientists employ it to comprehend the manner in which minerals deform and occasionally fail in response to drilling, completion, and production operations.[20]

Operators were significantly affected by Non-Productive Time (NPT) as a result of the stuck pipe, tight hole, and other well bore instability issues. Drilling operations are characterized by instability issues, which can be mitigated by conducting a thorough geomechanical analysis of the formation prior to the planning phase [28] . This task necessitates the use of wireline logs, seismic data, image log data, Pore pressure, stresses, and laboratory test data from experiments on core samples of the formation in order to generate MEM. A number of empirical correlations were used to derive geomechanical characteristics from log data. The mechanical earth modeling process is as follows :

1. Collect and prepare all necessary well data
2. Examine the lithology of the formation and compute the shale volume (V_{sh}) with Gamma Ray logs.
3. Determining rock strength parameters , elastic parameters and mechanical characteristics, including Young's Modulus, Poisson's Ratio, Uniaxial Compressive Strength (UCS), Tensile Strength, and Friction Angle using log data analysis.
4. Estimating Vertical stress (SV) using Density logs.
5. Estimating Pore pressure from Acoustic slowness logs
6. Determining the maximum and minimum horizontal stresses using empirical correlations,
7. Highlight safe mud weight using failure criteria (e.g., Mohr-Coulomb, Mogi-Coulomb)
8. Visualization of 1D mechanical earth model

III.1.1 Data Collection

Building a 1D Mechanical Earth Model (MEM) for wellbore instability study starts with data gathering, the first and most important phase. It means collecting a thorough data from laboratory measurements, drilling reports, and well logs. Key logs include density, acoustic, gamma ray, resistivity, and caliper logs, which enable the identification of formation characteristics including pore pressure, elastic moduli, lithology, and borehole expansion signals.[22]

III.1.2 The lithology of the formation

The lithology of a formation may be accurately defined by the analysis of well log data, especially Gamma Ray (GR) logs, which quantify the natural radioactivity of the rocks. Generally, elevated Gamma Ray measurements indicate the existence of shale or clay-dominant substances, while diminished readings imply purer, sandier lithologies. The shale volume (V_{shale}) is often determined using the linear technique, which calculates V_{shale} based on the normalized Gamma Ray index (I_{GR}). This indicator is calculated by juxtaposing the obtained GR values with recognized clean sand and shale baselines.[1, 2] The employed formula is:

$$I_{GR} = \frac{GR_{\text{log}} - I_{\text{clean}}}{GR_{\text{shale}} - I_{\text{clean}}} \quad \text{Eq III-1}$$

V_{shale} is typically derived directly from I_{GR} in younger formations or adjusted using empirical correlations, such as Larionov's correction for older rocks.[3] This methodology offers a quantitative foundation for interpreting lithological variations and facilitates reservoir assessment by accurately identifying shale content.

III.1.3 Rock strength parameters

In the construction of a 1D Mechanical Earth Model (1D MEM), rock strength is essential, as it directly influences the behaviour of the subsurface under natural and drilling induced stresses. This includes compressive, tensile, and shear strength.

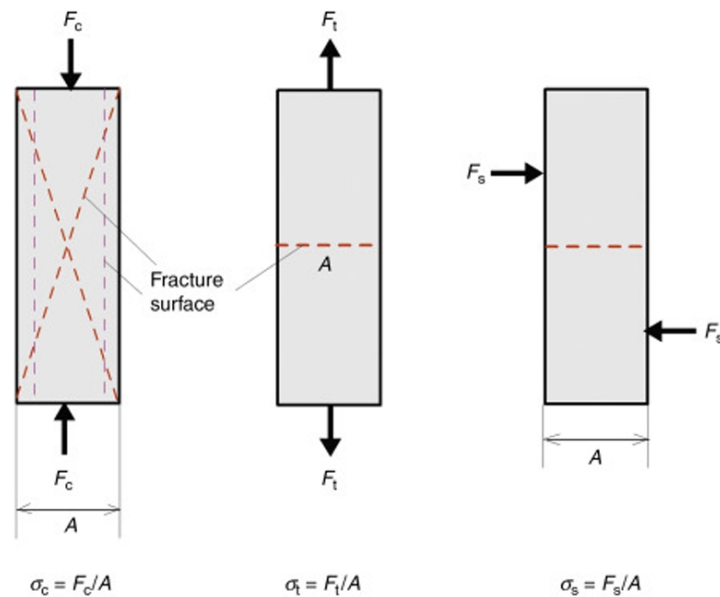


Figure III-1 In order to estimate these rock strengths, we rely on a combination of laboratory measurements, empirical correlations, and well log interpretations such as uniaxial

compressive strength (UCS), tensile strength (T0), cohesion (C0), and the coefficient o

III.1.3.1 Uniaxial compressive strength (UCS)

Uniaxial compressive strength (UCS) is frequently employed to evaluate the ability of rocks to withstand axial stresses in the absence of lateral support, and it is widely regarded as one of the most fundamental mechanical properties.[21] The load-displacement data generated from the uniaxial compression test may be used to identify the stress-strain curve of the rock sample, therefore establishing parameters such as unconfined compressive strength(UCS), Young's modulus, and Poisson's ratio from the curves.[23]

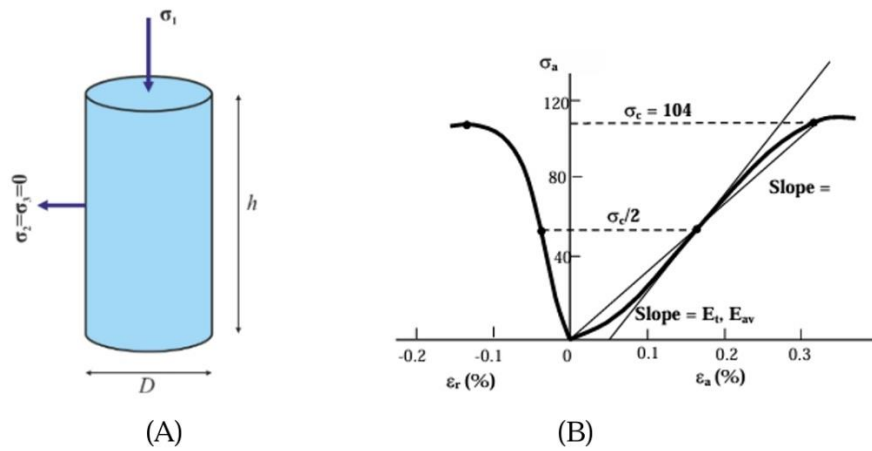


Figure III-2 (A) Uniaxial compression test. (B) Stress-strain curve and the calculation of the tangent intact rock modulus

Log Based Modelling is the most effective approach to derive UCS in the absence of primary data [35]. the UCS was determined through empirical correlation, which employs Acoustic Slowness (DT). As the well was located in a shale formation, Bradford provided empirical correlation.[24]

$$UCS = 2.28 + 4.1089 * E_{stat} \quad \text{Eq III-2}$$

where UCS is unconfined compressive strength (MPa), E_{stat} is the static Young's Modulus

III.1.3.2 Tensile strength (T_0)

The tensile strength of rock is a key mechanical property that tells you how much weight a material can hold without breaking when stretched.[25] When pressures below the tensile strength are put on a material and then taken away, it may return to its previous shape and size in whole or in part. But as the force gets close to the tensile strength, the material behaves in a very different way. The plastic bending process starts and gets stronger in flexible materials. This causes a neck to form, which in turn causes the material to break.[26]

Presently, techniques for assessing the tensile strength of rocks are mostly categorized into direct and indirect. For direct measurement, tensile tests are done directly on rock samples. This gives tensile strength values that are most close to the real value. However, because rocks are so fragile, doing direct tensile tests in the lab is often not possible or even possible but very hard to do. Because of this, secondary tests like the Brazilian splitting test and the three-point bending test are used more often.[27]

III.1.3.3 Cohesion (C_0)

cohesion is a major quality of materials. Mechanically, it is the energy needed to fracture a totally brittle material along a molecularly smooth crack. Then the cohesion is the energy held in the links between the two surfaces of the material.[28] its commonly expressed through the Mohr-Coulomb failure criterion as :

$$\tau = C_0 + \sigma \tan (\phi) \quad \text{Eq III-3}$$

where τ is the shear stress at failure, C_0 is the cohesion, σ is the normal stress, and ϕ is the internal friction angle.

III.1.3.4 Internal Friction angle (ϕ)

The internal friction angle is One of the significant factors is considered a characteristic attribute of granular soils. The capacity of a rock or soil mass to endure shear stress is defined by the angle of internal friction. Upon the occurrence of failure due to shearing stress (τ), the angle (ϕ) between the normal force (σ) and the resultant force (R) is referred to as the angle of internal friction. It can be determined in the laboratory by the Direct Shear Test or the Triaxial Stress Test.[29]

III.1.4 Rock elastic parameters

Rock elastic characteristics (e.g., elastic modulus and Poisson's ratio) are the most important design features in geotechnical. These properties can be obtained through laboratory tests and are subsequently referred to as static elastic properties. This process only provides information regarding the depth from which the core was extracted. To consistently receive information, the properties are typically derived from sonic log measurements. These are referred to as dynamic elastic properties.[30]

III.1.4.1 Young's Modulus (E)

Young's modulus (E) is a fundamental material property that delineates the correlation between the dimensionless elongation of a material, known as strain (ϵ), and the force applied per unit area, referred to as stress (σ).[31] It can often be demonstrated by the rigidity of a material or its tendency to flex or stretch.

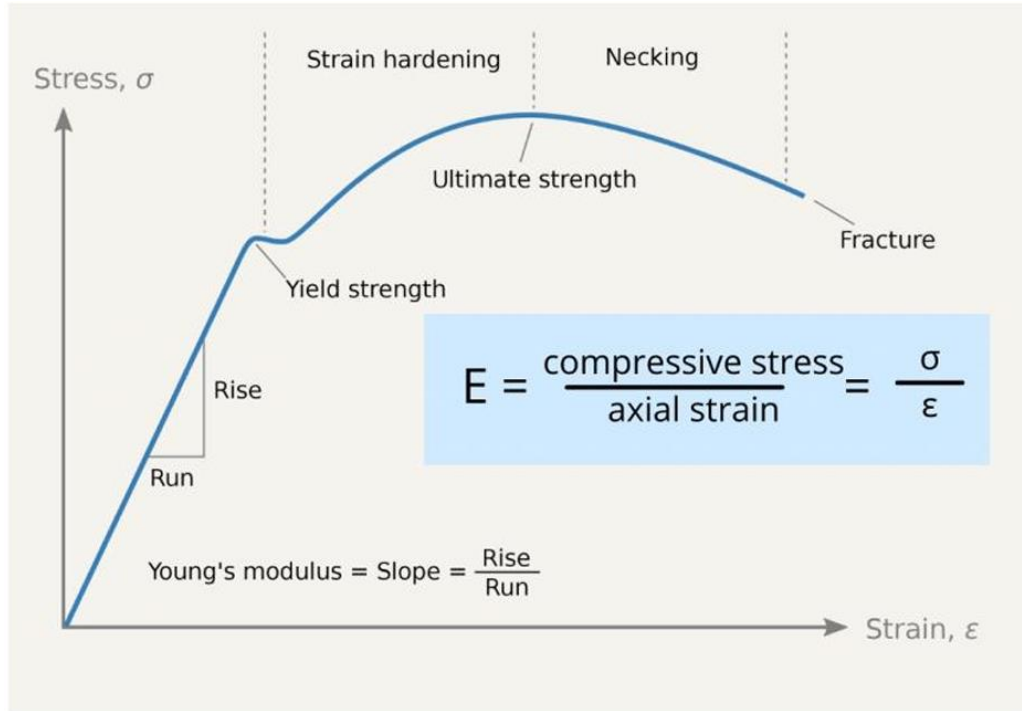


Figure III-3 Rock elastic parameters

The fundamental principle is that a material experiences elastic deformation when it is compressed or extended, and it reverts to its original shape upon the removal of the burden. In comparison to a rigid material, an elastic material experiences a greater degree of deformation. A solid is elastic if its Young's modulus is low. Otherwise is inelastic or stiff if its Young's modulus is high.[32]

Young's modulus compares tensile or compressive stress to axial strain. The formula for Young's modulus is:

$$E = \frac{\sigma}{\epsilon} \quad \text{Eq III-4}$$

Alternatively, Young's modulus can be determined through dynamic or static methods, using equations based on sonic log data and core measurements.

$$E_{\text{dynamic}} = \left[\frac{\rho}{\Delta t_s^2} \right] \left[\frac{3\Delta t_s^2 - 4\Delta t_p^2}{\Delta t_s^2 - \Delta t_p^2} \right] \quad \text{Eq III-5}$$

Eq

$$E_{\text{static}} = 0.414 * E_{\text{ayn}} - 1.05$$

where Δt_p and Δt_s is Acoustic and Shear slowness, ρ is Bulk Density.

III.1.4.2 Poisson's Ratio (ν)

The Poisson's ratio is the negative ratio of a material's transversal or lateral strain to its longitudinal strain when stressed. Simply, it evaluates a material's capacity to thicken when squeezed and thin when stretched.[33]

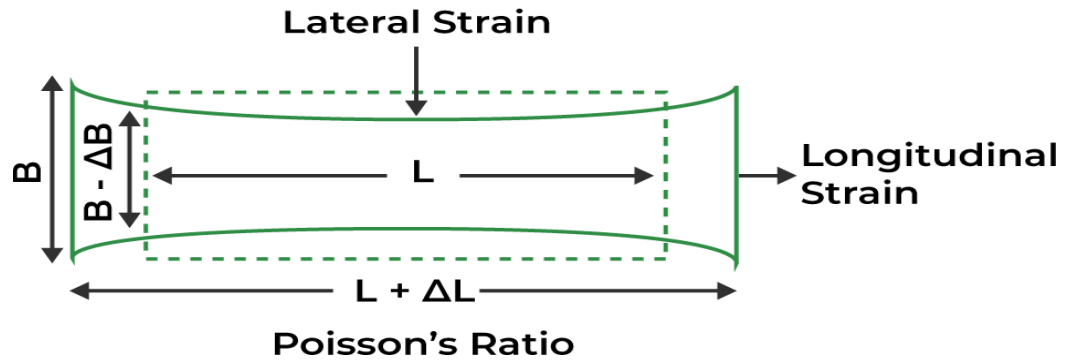


Figure III-4 Poisson's ratio

III.1.5 Determination of in-situ stress

Three major stresses operate on the subsurface: vertical or overburden stress, maximum horizontal stress, and minimum horizontal stress. The relative magnitudes of these primary stresses regulate the bulk of the subsurface phenomenon.[34] In-situ stress is the natural stress that is already contained in the rock before it is drilled, dug up, or changed by outside forces. The in-situ pressures start in the earth's crust because of many things, mainly the weight of the rocks on top of each other and the movement of tectonic plates.[35]

As seen in Figure III.5, the determination techniques of in-situ stresses may be grouped into three types. The loading technique disturbs the in-situ stress state in the rock, for example, by injecting high pressure fluid into the formation to generate cracks. The relief technique consists of partly or totally isolating the rock sample from the surrounding rocks and watching the natural rock reaction to the in-situ stress. Geological and geophysical techniques among others may help determine the in-situ stress in the rock. The techniques depend on the measurements of any change in rock volume or form (Strain) because stress cannot be measured directly.[35]

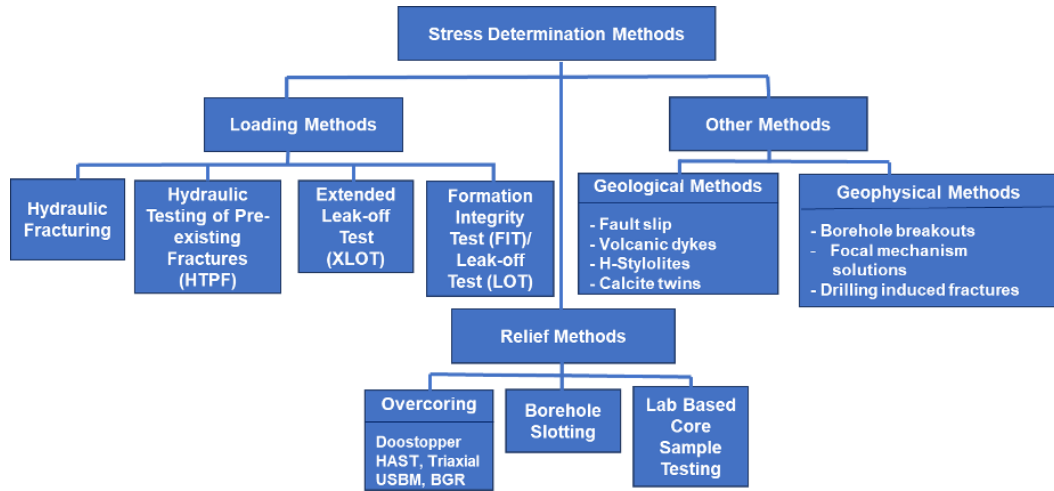


Figure III-5 Summary of the stress determination methods.

III.1.5.1 Overburden stress

The overburden stress is always in the vertical direction and is caused by the weight of all the rocks above the site of interest. The bulk densities extracted from the density log for a column of sediments can be integrated to determine the overburden stress values,[36] the formula of the overburden stress could be showed as:

$$S_v = \int_0^z \rho(z) * g * dz \quad \text{Eq III-7}$$

where: S_v is the vertical (overburden) stress at true vertical depth and measured in Pascal (N/m²) unit, $\rho(z)$ is bulk density as a function of depth (gm/cm³), g is the gravitational constant (9.8 m/s²) and dz is the depth (m).

III.1.5.2 Maximum and minimum horizontal stresses

The minimum and maximum horizontal stresses (S_{hmin} and S_{hmax}) are two of the three major stresses essential for any geomechanical investigation, particularly in wellbore instability analysis.

S_{hmin} and S_{hmax} may be directly evaluated using the leak off test (LOT), extended leak off test (XLOT), or indirectly approximated using well log data.[37]

The minimum horizontal stress can be established through direct measurements, utilizing established methods such as micro-hydraulic fracturing, or its oil field counterparts, including mini frac, leak-off test (LOT), or extended leak-off test. This stress is generally equivalent to the fracture closure pressure, which can be identified following shut-in on the decline curve of a leak-off test.[38]

We can express the minimum horizontal stress σ_{hmax} using poroelastic theory as:

$$\sigma_h = \left(\frac{\nu}{\nu - 1} \right) (\sigma_v - \alpha P_p) + \alpha P_p + \left(\frac{E}{1 - \nu^2} \right) (\epsilon_h - \nu \epsilon_H) \quad \text{Eq III-8}$$

Where σ_v represents the vertical stress or overburden pressure, α is Biot's coefficient which accounts for the influence of pore pressure on effective stress, and P_p is the pore pressure within the formation. The term ν denotes Poisson's ratio, a measure of the material's lateral deformation relative to axial deformation, while E is Young's modulus, representing the elastic stiffness of the rock.

Finally, ϵ_H and ϵ_h correspond to the major and minor horizontal strains, respectively, reflecting deformation in the horizontal plane.

The maximum horizontal stress, in contrast to the minimum horizontal stress, cannot be measured directly and is generally regarded as the most challenging component of the stress tensor. The process necessitates an comprehension of pore pressure, calibrated rock strength, vertical stress, and minimum horizontal stress data. The estimation of maximum horizontal stress can be derived from image logs, the frictional limit to stress, drilling induced fractures (DIF) data, micro frac data, and calliper data.[30]

the expression for maximum horizontal stress is presented below, following the principles of poroelastic correlation:

$$\sigma_h = \left(\frac{\nu}{\nu - 1} \right) (\sigma_v - \alpha P_p) + \alpha P_p + \left(\frac{E}{1 - \nu^2} \right) (\epsilon_H - \nu \epsilon_h) \quad \text{Eq III-9}$$

Obtaining a precise horizontal stress profile from well data calls for checking the profile with a stress value known from the well. Usually, this comes from an in-situ stress test like a mini-frac or leak-off test. Many deep oil wells, however, lack these tension readings, either due to technological limitations or cost. Without this calibration, the anticipated stress values from logs might lose dependability, which would make it more challenging to use them in fracture design or wellbore stability operations.[39]

III.1.6 Pore pressure

A solid matrix and pores that are saturated with water or other fluids make up the porous media in a hydrocarbon formation. Pore pressure, also known as formation pressure in hydrocarbon reservoirs, is the force exerted on the rock pores' walls by the formation fluids.[40]

The drill stem test (DST) represents the most accurate technique for the direct measurement of pore pressure. Additionally, the modular dynamic formation test (MDT) and repeat formation test (RFT) are effective methodologies for this application. Additionally, this pressure can be quantified using tests such as measurement while drilling (MWD), logging while drilling (LWD)(Sonic and resistivity logs

can be used to identify it), and pressure while drilling (PWD). meanwhile, a diagnostic fracture injection test (DFIT) is utilized to evaluate this in low-permeability formations. These experiments are characterized by high costs, significant time requirements, and applicability limited to shallow depths.

To calculate pore pressure we use Eaton's method, which uses sonic log:

$$P_p = OBG - (OBG - P_{hyd}) \left(\frac{\Delta T_n}{\Delta T_{log}} \right)^3 \quad \text{Eq III-10}$$

where OBG is overburden stress gradient, P_{hyd} is hydrostatic pore pressure gradient and log refer to normal and measured values of ΔT at each depth. ΔT_n is the Normal Compaction Trend plotted against ΔT .

III.1.7 Safe mud weight window

Failure criteria, such as Mogi-Coulomb or Mohr-Coulomb, define the stress levels at which the rock around the wellbore may fracture (causing tensile failure) or collapse (causing shear failure).

These standards define the lowest and maximum allowed mud weights while drilling. A borehole could collapse if the mud weight is too low because the formation cannot handle the stress, which defines the bottom limit of the safe mud weight window. But too large mud weight may fracture and exceed the tensile strength of the formation, therefore defining the maximum limit of the window, see Figure II-9 Relationship between mud weight and wellbore failures, modified from Well Inclination and Azimuth[33]

Therefore, the failure criteria is the basis for defining the safe range of mud pressure that ensures wellbore stability without causing lost circulation or structural damage.

CASE STUDY

WELL 1

III.2 The realization of 1D Mechanical Earth Model

III.2.1 Data collection

Construction of the 1D MEM requires data from many sources, such as laboratory tests, well logs and daily drilling reports. The resulting model is a reliable and accurate geomechanical representation of the wellbore region. Information gathered helps in estimating rock strength, in-situ stresses, pore pressure and wellbore stability. The following figure shows the different types of data required to create the 1D MEM.

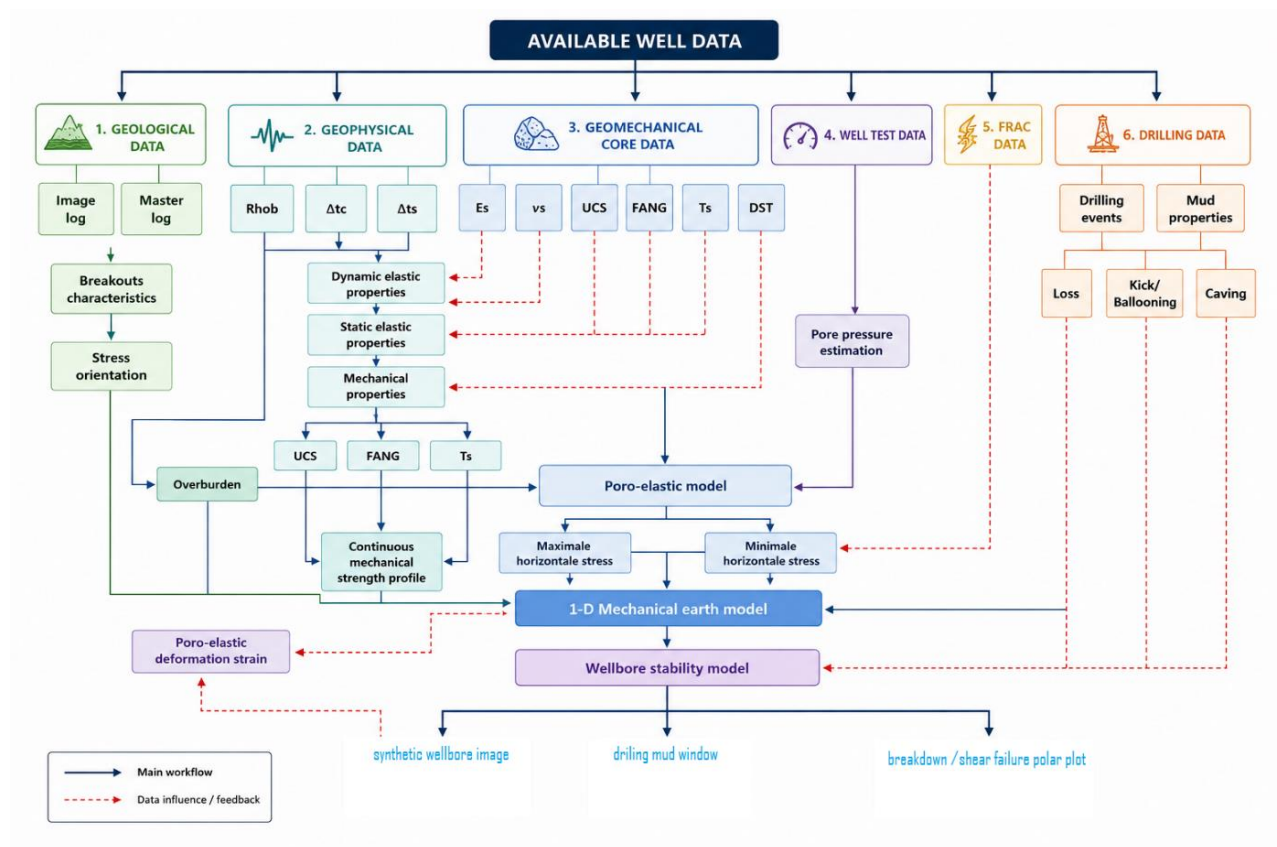


Figure III-6 1D MEM building flowchart

III.2.2 Overburden stress

Given the absence of the bulk density log, an extrapolation algorithm has been employed to reconstruct a complete overburden stress profile for the available wells at the study area.

A data inventory is generated and where density logs intervals are missing, a complete set of synthetic density logs is established from the master log dataset: GR, Sonic and other available logs.

The synthetic density logs are correlated with the associated depth intervals to match their density value with the appropriate formation having similar lithological characteristics.

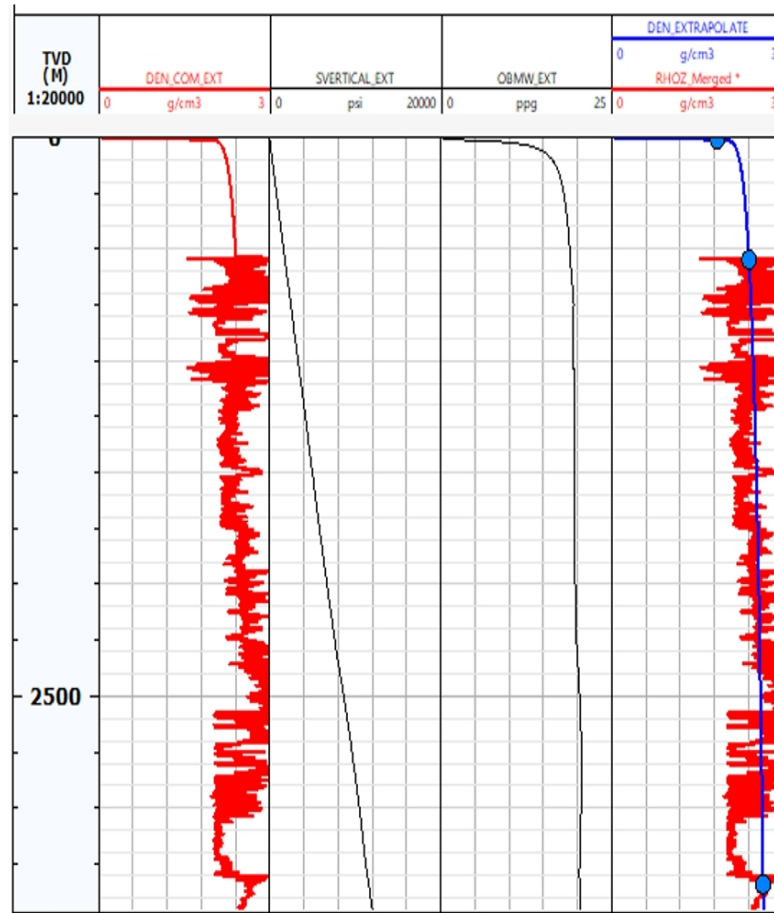


Figure III-7 Overburden stress

III.2.3 Pore pressure estimation

To determine the pore pressure gradient Drill Stem Test (DST) is carried out to evaluate the reservoir pressure conditions. In addition, kicks and trip gas are analyzed to further validate the pore pressure profile.

Drilling Well-1 with mud weight of 1.19 sg resulted in a kick event. Further drilling was continued with mud weight of 1.30 sg, which provided well control and drilling stability. The DST recorded the reservoir pressure of 285.32 bar at 3895 m depth of well-1, from which the reservoir pore pressure gradient is calculated to be 0.0748 bar/m as shown in the figure.

The present study provides useful information about the in-situ stresses of sand shale sequence from well-1 in the absence of direct measurement methods such as borehole breakout and leak off tests.

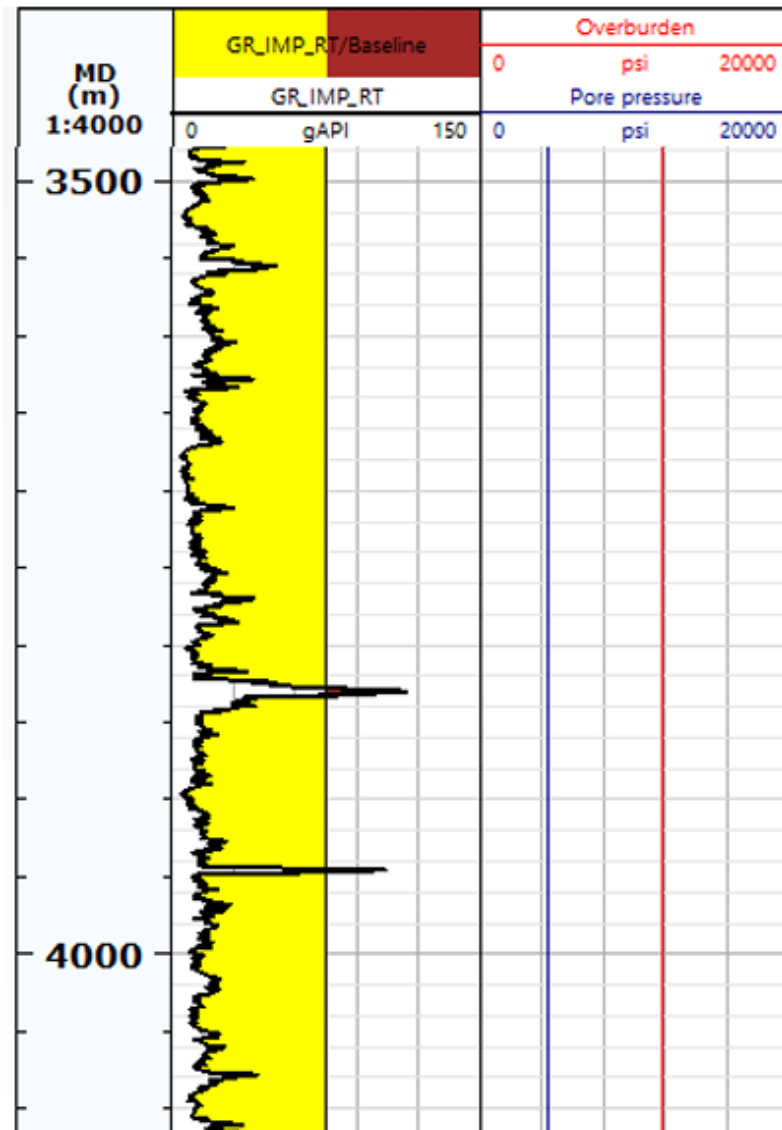


Figure III-8 Pore pressure estimation

III.2.4 Rock elastic properties

In rock mechanics, there are two basic parameters - Young's modulus and Poisson's ratio - which are available in both changing and static conditions. In this study, it is assumed that the rock formation exhibits isotropic elastic behavior.

Changing elastic properties from well log data such as bulk density logs and sonic logs (compressional and shear interval transit times, denoted ΔT_c and ΔT_s respectively) have been determined from compressional and shear sonic.

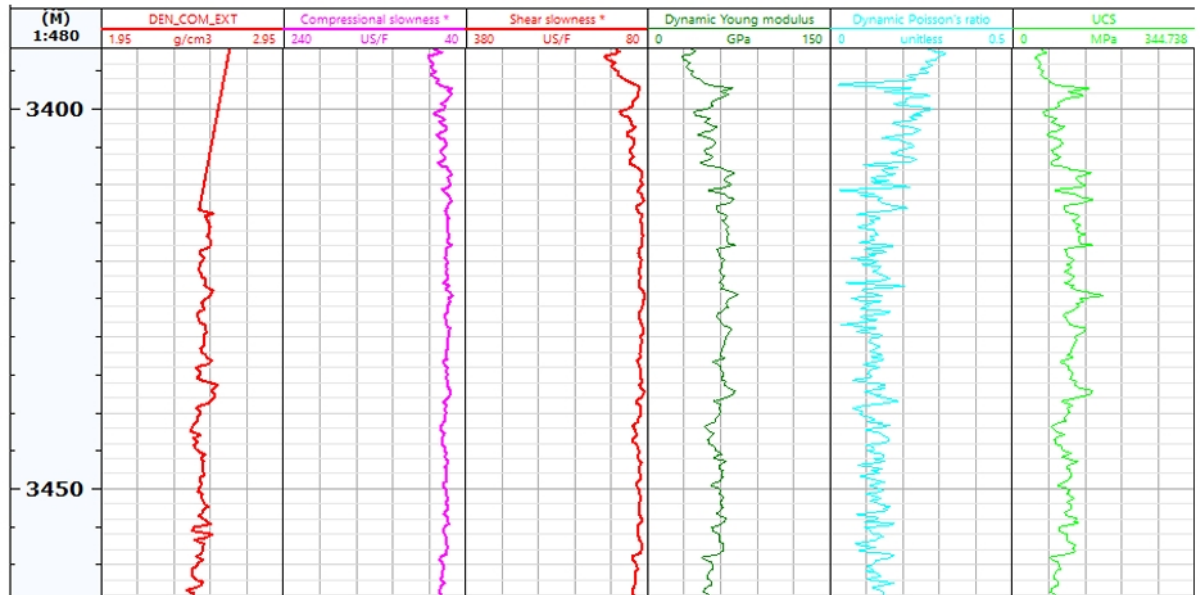


Figure III-9 Dynamic Young modulus and dynamic Poisson's ratio

The dynamic Young modulus has to be correlated to the static property from the mechanical core test of the well by using the following regression (with $R^2 = 0.9073$)

$$E_{sta} = 7.7012 * e^{0.0317 * E_{dyn}} \quad \text{Eq III-11}$$

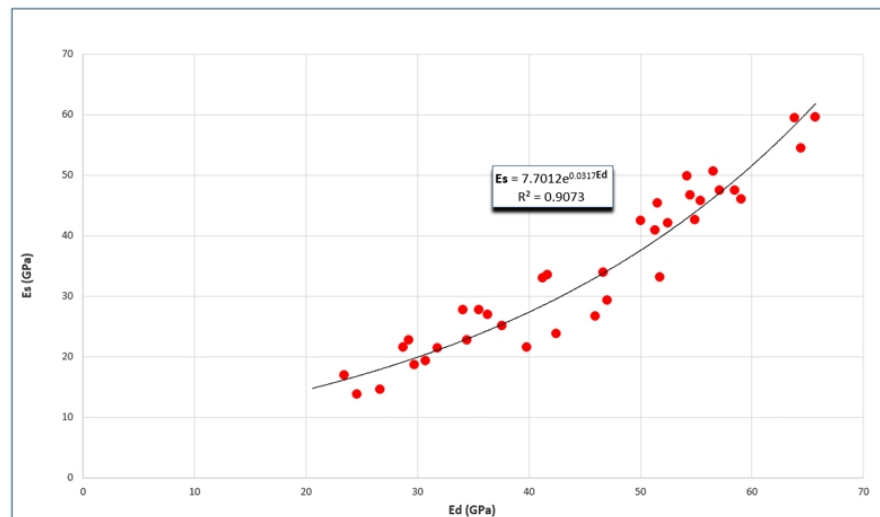


Figure III-10 Variation of static Young's modulus static depends on dynamic Young's modulus

Based on the sonic log below for dynamic Poisson's ratio:

$$V_{sta} = V_{dyn} \quad \text{Eq III-12}$$

Young's modulus ranges from 35 GPa up to 55 GPa.

The dynamic Poisson's ratio equals the static Poisson's ratio of 0.15.

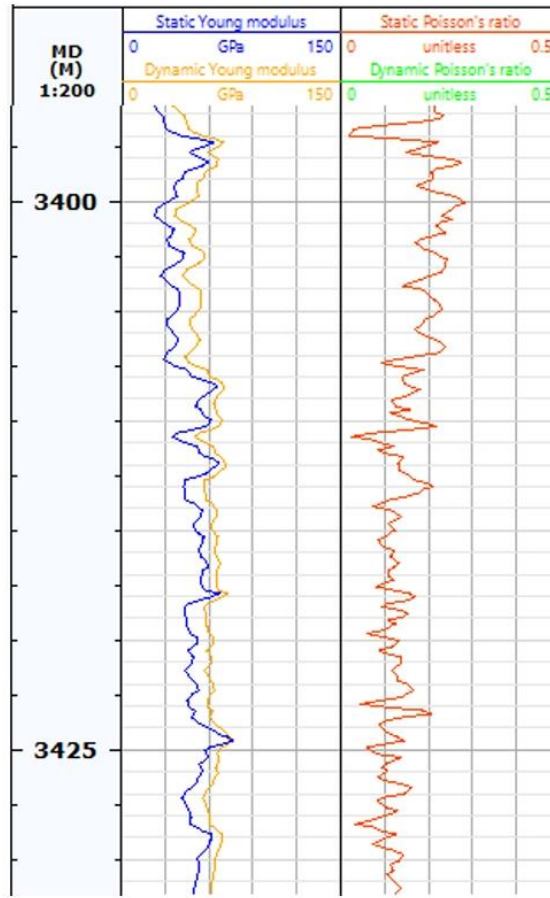


Figure III-11 Young's modulus and Poisson's ratio

III.2.5 Rock strength properties

III.2.5.1 Unconfined compressive strength

The mechanical core tests from Well-1 provided the input parameters for estimating the unconfined compressive strength (UCS). In this paper, the researchers derived UCS using an empirical connection with the static Young's modulus to create a continuous UCS profile along the wellbore.

The empirical connection used is:

$$UCS = 2.1595 * E_{stat} + 6.3235 \quad \text{Eq III-13}$$

The coefficient of determination $R^2 = 0.9073$, meaning that there is a important relationship between the variables.

According to the log interpretation below, the unconfined compressive strength (UCS) of the formation ranges from about 80 to 135 MPa.

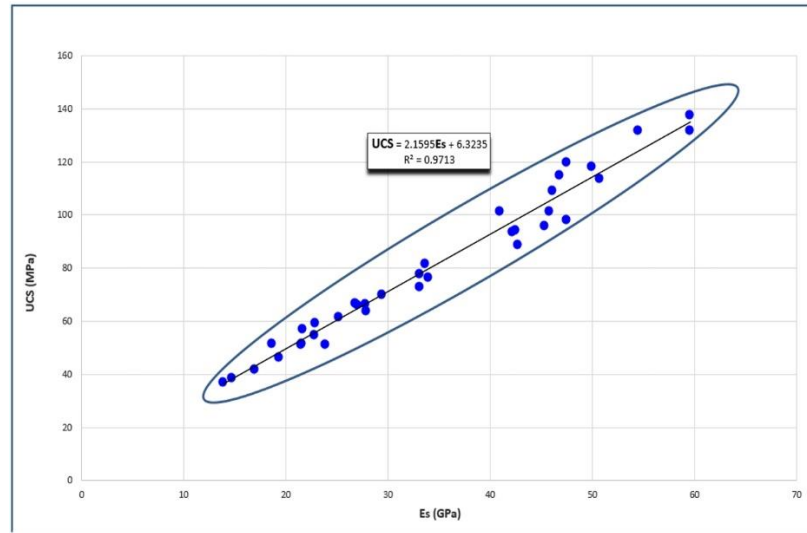


Figure III-12 Variation of UCS depends on static Young's modulus

III.2.5.2 Friction angle

Mohr's circle experiments were done on core samples taken at the same depth from Well-1 and the laboratory data produced two reference points to calibrate the linear relationship between gamma ray (GR) log and internal friction angle.

The results show that the internal friction angle of the formation is 36° to 40°.

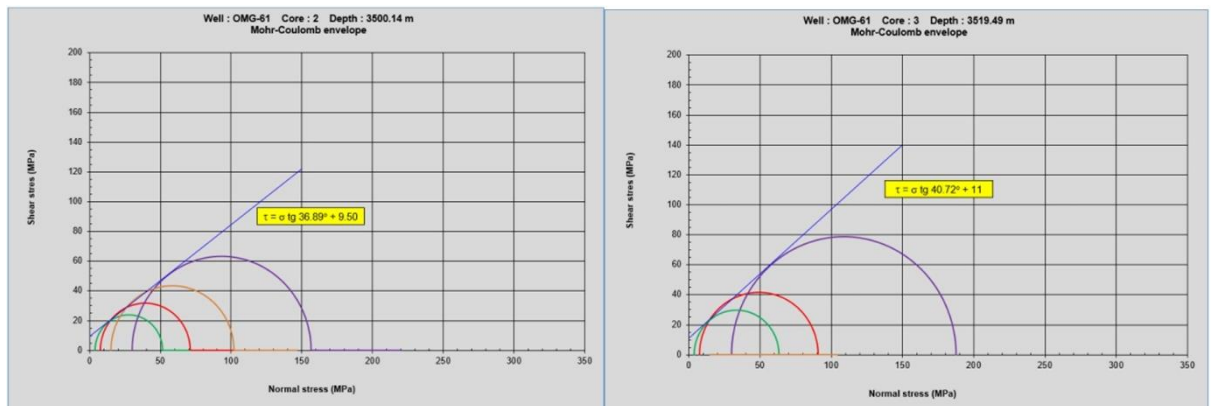


Figure III-13 Friction angle from Mohr's circle

III.2.5.3 Tensile strength

The tensile strength of the rock was estimated by scaling the unconfined compressive strength (UCS) to the results of Brazilian tensile strength tests. Laboratory measurements in this case study indicated that the tensile strength is about 5% of the UCS.

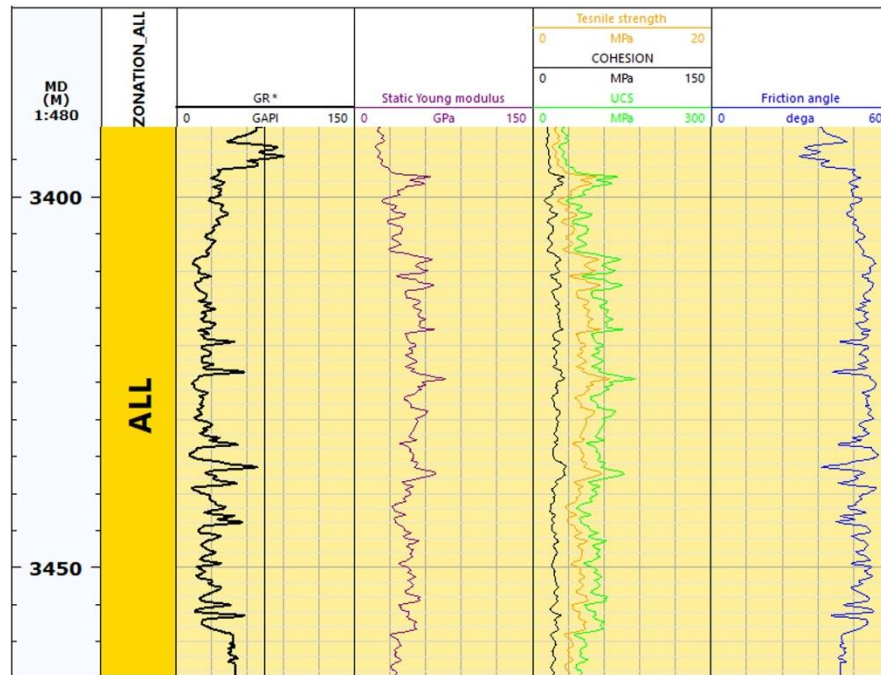


Figure III-14 Tensile strength

III.2.6 In-situ horizontal stresses

Maximum horizontal stress and minimum horizontal stress are represented by the poro-elastic isotropic model using the equations mentioned before. The in-situ stress regime in the reservoir has been characterized as strike-slip faulting regime as shown in the chart below where:

$$\sigma_H > \sigma_v > \sigma_h$$

The minimum and maximum horizontal strains (ϵ_{hmin} and ϵ_{Hmax}) were calibrated with field data and operational data including mud losses, DST data, fracture data and wellbore image logs.

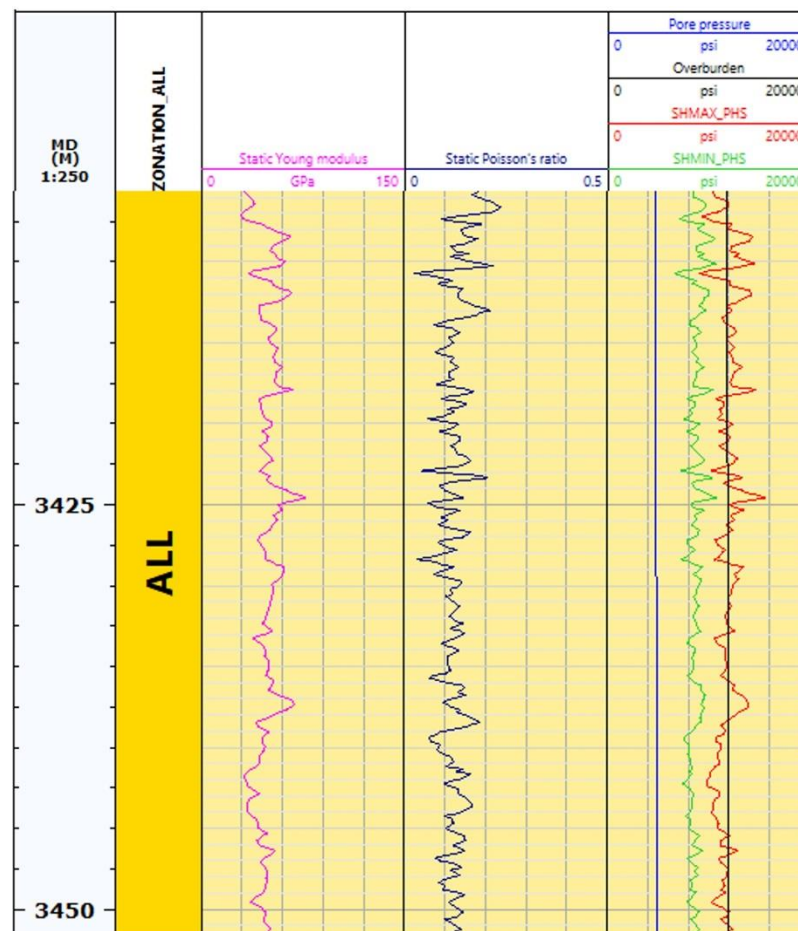


Figure III-15 Maximum and minimum horizontal stress

III.2.7 In-situ horizontal stresses orientations

The azimuth and width of wellbore breakouts were determined from the borehole image logs in this study. A review of the existing image logs indicated that no drilling induced fractures (DIFs) were present.

The chart below is an example of the identified breakouts used to determine the orientation of the in-situ stresses. Using the breakout interpretation, the orientation of the minimum horizontal stress (σ_h) was estimated to be between 30° and 40° in the NE–SW direction.

Thus, the maximum horizontal in-situ stress (σ_H) is oriented in the perpendicular direction, which is approximately between 120° and 130°.

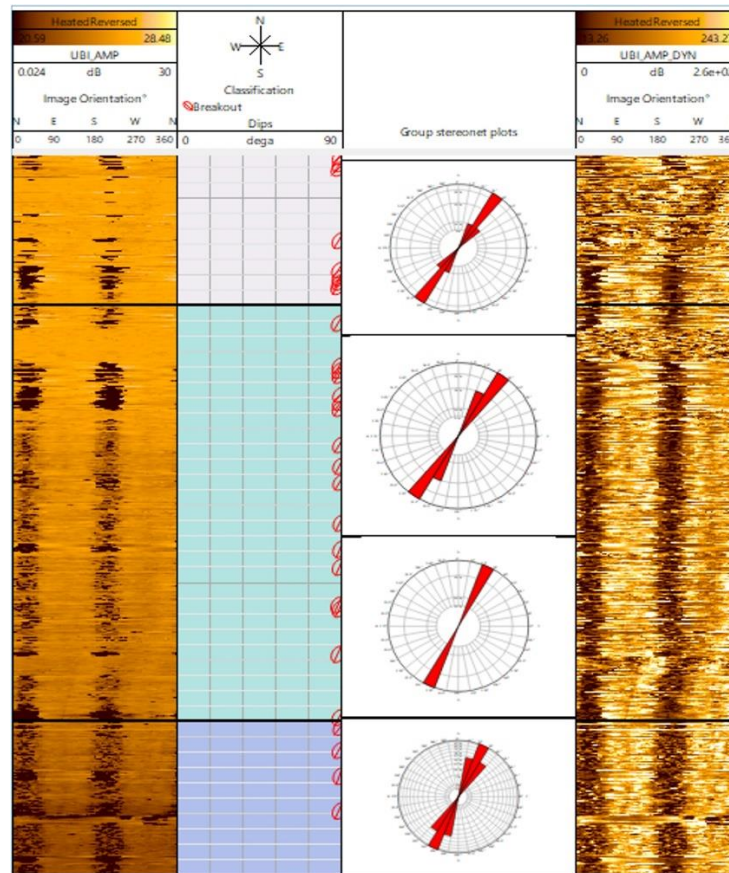


Figure III-16 Borehole image

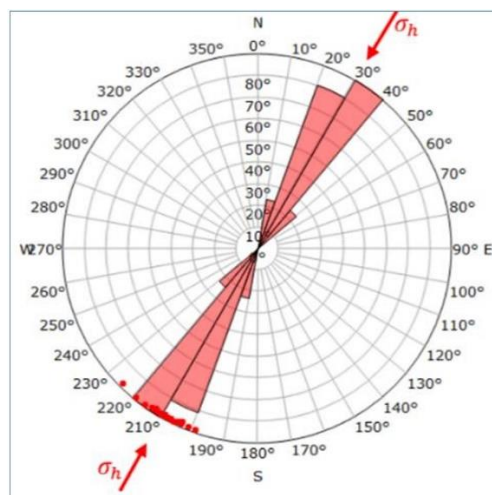


Figure III-17 Orientation of the minimum horizontal stress

III.2.8 Wellbore Stability Analysis

Using the Mohr-Coulomb criterion equations discussed in Chapter II, the wellbore stability analysis was conducted, which enabled determination of shear failure gradient, pore pressure gradient, fracture gradient, and breakout gradient. The breakout analysis is recorded below and allows for

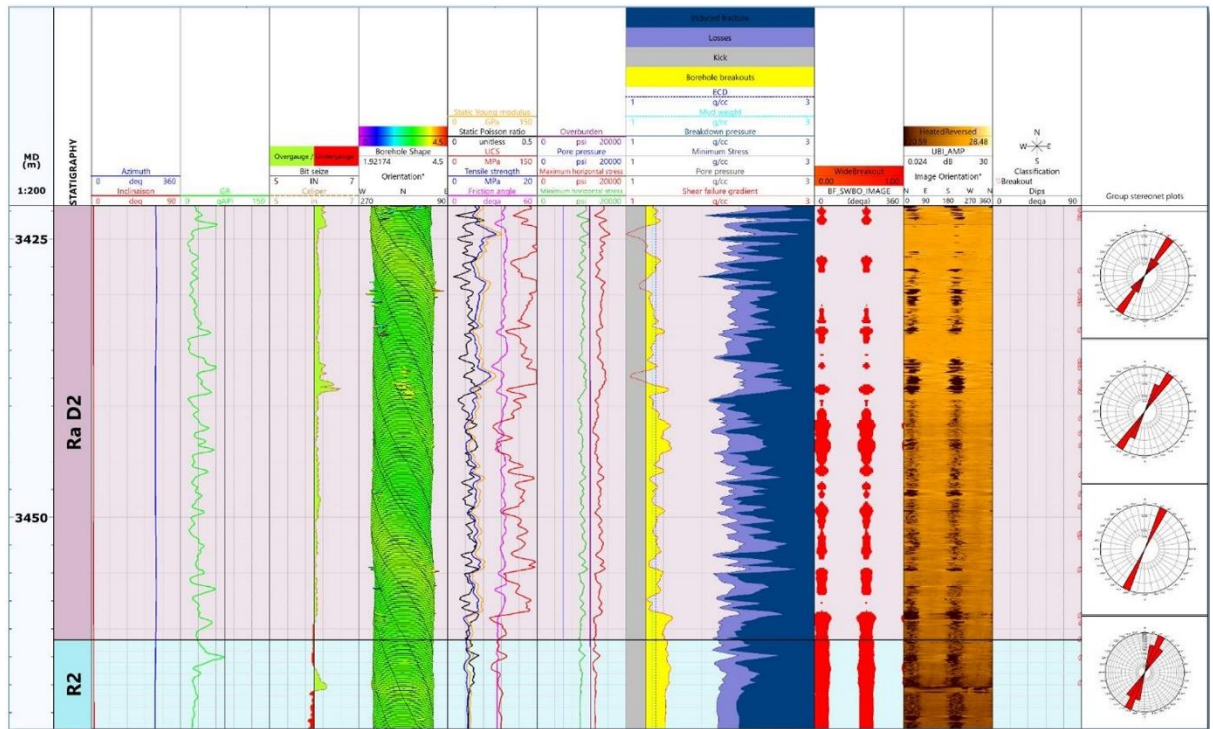


Figure III-19 Final 1D MEM and wellbore stability modeling

III.2.9 Failure and stability discussion

The image below shows how pressure and mud density influence a borehole's condition and its necessity for borehole stabilization. As is shown in the image below, when a borehole mud density is too low, it increases the likelihood of shear failure, and also introduces the potential for kicks to occur. Conversely, if a borehole mud density is too high (above the minimum horizontal stress), it can result in lost circulation due to a natural fracture creating an uncommunicated channel to the mud level. Finally, if a borehole mud density is greater than the minimum horizontal stress, it could create a fracture in the formation. Therefore, to provide stable wellbores, the borehole mud density should be appropriately evaluated.

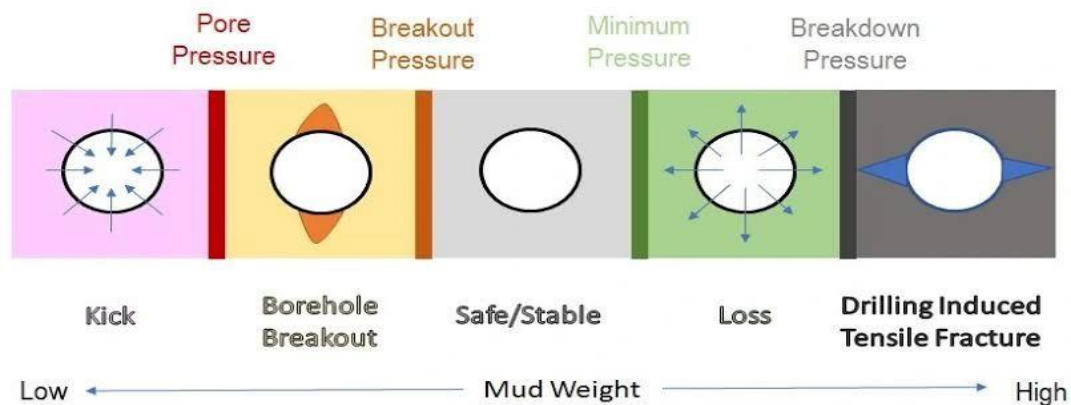


Figure III-20 Different mud windows in stability plot

III.2.10 Results and discussion

From the wellbore stability model just described, these points emerge:

- Down near the reservoir, forces shift sideways more than anything else. Pressure builds where rock layers slide past one another. This kind of movement shapes how cracks form underground. Instead of pulling apart or squeezing straight on, things grind laterally here. Faults develop under this constant side-to-side push
- $\sigma_H > \sigma_v > \sigma_h$
- Beneath the surface, pressure shifts steadily - climbing from 0.81 pounds per square inch each foot up to 0.95. That rise defines how rock layers respond when stressed deep underground.
- Simulation of the wellbore shows these ranges for stable mud weight inside the reservoir area:
- Between 1.47 and 1.89 g/cm³, mud weight keeps formations intact while staying within a secure operating zone. That span avoids harming the rock structure even slightly. Pressure stays balanced because the fluid is just heavy enough, yet never too dense. This narrow limit prevents cracks or leaks underground. Stability comes from staying inside these boundaries without drifting higher or lower.
- Between 1.22 and 1.89 g/cm³, mud weight holds up just fine - yet cuts rock permeability by nearly 5%. Still, that drop comes with the territory. Performance dips a bit, sure, but stays within limits. Not ideal, yet workable under real conditions. Flow capacity takes a small hit, nothing worse. This zone keeps functioning, even with the trade-off.
- Beyond the vertical part, pressure needed to split rock turns out stronger in horizontal stretches - this hints that sideways boreholes handle pulling forces better. What stands out? Horizontal paths resist breaking under tension more than up-and-down ones.
- Out of nowhere, small changes in how sentences are built add a quiet kind of rhythm. Not every line follows the usual path - some twist left when expected to go right. This uneven pace keeps things feeling loose, almost accidental. Machines scanning for patterns stumble here, unable to lock onto a fixed form. Even punctuation takes odd turns, spacing out differently without warning. The whole piece avoids repetition like it's avoiding noise. Nothing lines up too neatly, which makes it feel lived-in. Detection tools look for consistency and come away empty-handed.

III.2.11 Modelling uncertainties

Among other things that emerged in the process of creating the 1D MEM model and analyzing wellbore stability are the following uncertainties:

- Pore pressure uncertainty has a great effect on the estimation of both in-situ and near-wellbore stresses.
- Also, uncertainties related to the estimation of the elastic parameters of the formations were revealed. Such uncertainties appear due to different reasons, one of which is the anisotropy of the reservoir section. While it was considered isotropic in this study, according to the dipole sonic log data, anisotropy of the reservoir section is evident. The impact of such anisotropy could be very significant concerning the result, particularly Young's modulus ($E_h \neq E_v$) and Poisson's ratio ($\nu_h \neq \nu_v$).
- Uncertainties in estimating the magnitudes of the in-situ horizontal stresses also appeared, mainly due to pore pressure uncertainty and estimation of elastic parameters. An additional effect could appear due to the anisotropic nature of the formation.

CASE STUDY

WELL 2

III.3 The realization of 1D Mechanical Earth Model

III.3.1 Section I

A closer look begins here - at how engineers built a vertical Mechanical Earth Model for Well-2, chosen as the test site among tight rock layers in Hassi Messaoud. Drilling sideways through those dense zones meant lining up the borehole along the weakest horizontal push (σ_h), helping oil flow better due to smarter placement.

Deep underground, rock layers sit tight and resist flow, so cracking them open helps release more oil or gas. A test hole curves like a hook through the earth, gathering readings along its path instead of rushing straight down. Information collected there shapes how future wells are built and treated. Pressure points and rock behavior come into focus only after sensors record what lies beneath.

One goal stands out here. Building a one-dimensional rock behavior model after drilling ends, using data from a nearby well. That setup helps see how forces press across the area more clearly. Direction matters. So does strength. Both show up better through this method. Properties like stiffness and resistance in underground layers become easier to pin down. Details about pressure within the ground come into sharper view too. Each piece fits together, guided by actual measurements pulled from the drilled path.

Later on, the geomechanical setup helps build a pre-drill 1D MEM tailored to the pilot well's intended horizontal stretch. Once fresh logging details come in, adjustments follow - fine-tuning both model accuracy and settings for the lateral borehole phase.

III.3.1.1 Well information and profile

Down in the Hassi Messaoud field sits Well-2, built with two parts: first it angles sideways, then stretches flat. While one piece leans, the next runs level beneath the ground.

Down near the start, the drill angled up about 25 degrees, pointing northeast. A fluid density of 1.25 sg guided operations through that stretch. Reaching roughly 3100 meters marked a shift - curving began from there. Bending downward added close to 50 meters vertically by the time the path straightened again. At its deepest point along the slant, it hit 3370 meters on tape, while standing at 3360 meters under true vertical measure.

After that, drilling pushed further down into a new target zone. From roughly 3315 meters true vertical depth, it moved past 3381 meters, eventually hitting 3412 meters when tracking the full curve of the hole. Instead of changing angle much, the drill stayed near horizontal - almost straight up and

down - while shifting direction slightly toward 37 degrees on the compass. Stability held firm across this stretch, which ran longer than 100 meters, even though nothing changed in how heavy the drilling fluid was.



Figure 0-1 Wells locations map

III.3.1.2 Overburden stress

Back near Well-1, old data recordings helped build a steady flow of information. Starting where one phase ended, the next bit was stretched forward to bridge empty stretches. Gaps between drilling stages got covered that way. Stitched piece by piece, the record stayed unbroken.

A full vertical stress profile came together through this method, keeping the stress log consistent along every part of the well zone while also making geomechanical analysis more trustworthy.

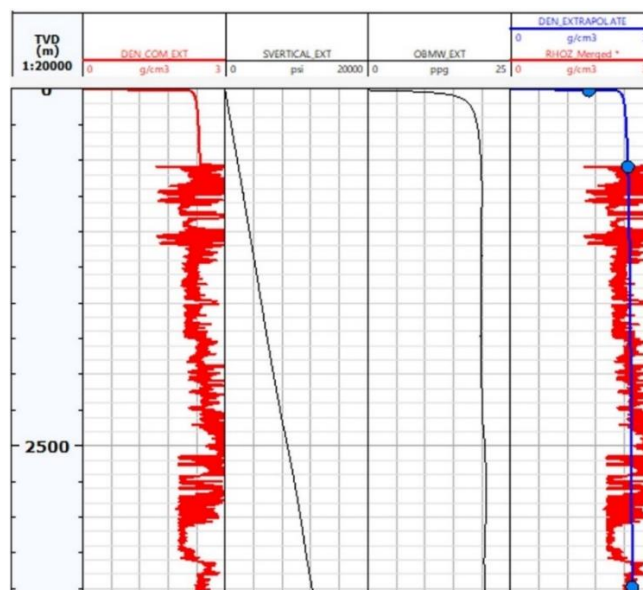


Figure 0-2 Overburden stress

III.3.1.3 Pore pressure

A pressure difference of 0.0791 bar per meter applied here. Drilling proceeded with a mud density at 1.45 specific gravity - this value helped shape how pore pressure got estimated.

Pore pressure values along the well path were mapped using this method. At total depth - 3381.97 meters - the measured pressure sits near 277.58 bar.

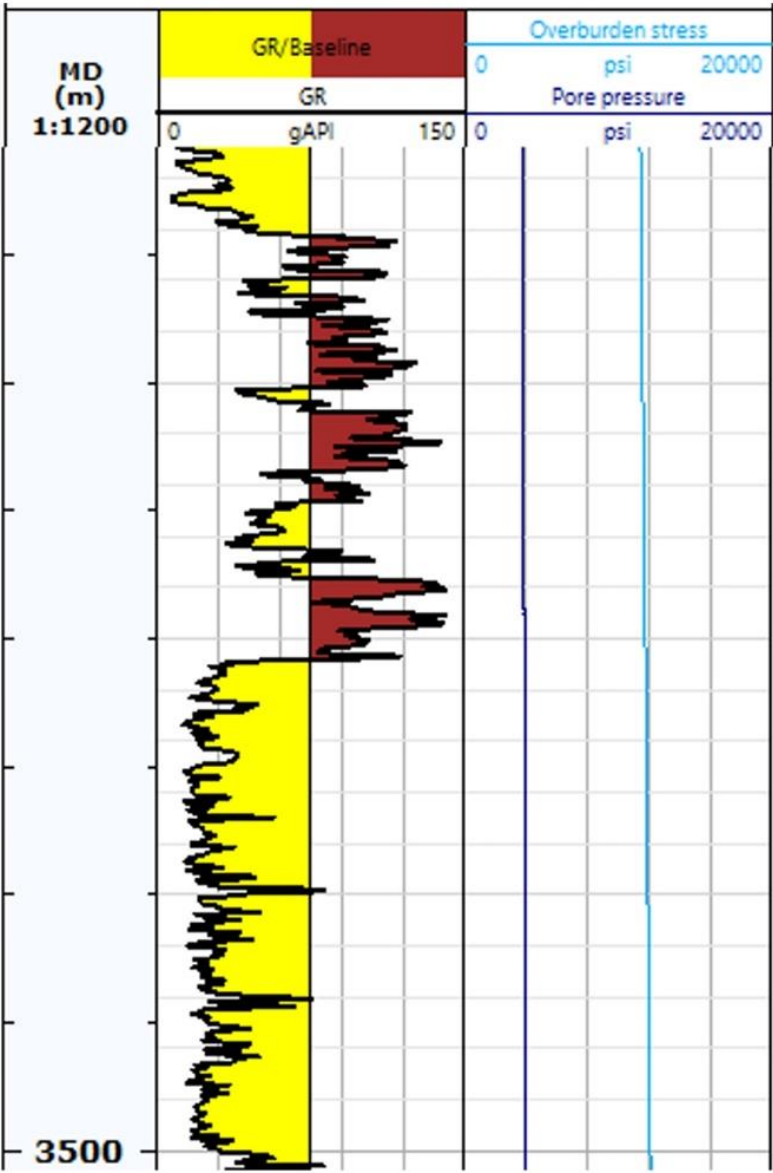


Figure 0-3 Pore pressure estimation

III.3.1.4 Rock elastic properties

Out of step with surface tests, the rock's stretch and squeeze traits came alive through density records tied to sound-speed traces. Following patterns spotted deep in Well-1, adjustments leapt from bouncy measurements to firm, real-world stiffness values.

Looking at the sonic logs, it turns out the static Poisson's ratio matches the dynamic one here. Though not always true, in this situation they line up closely. Because of how the data behaves, treating them as identical makes sense. Where differences might show up, none appear clearly in these results. So under these conditions, using one for the other works without major error.

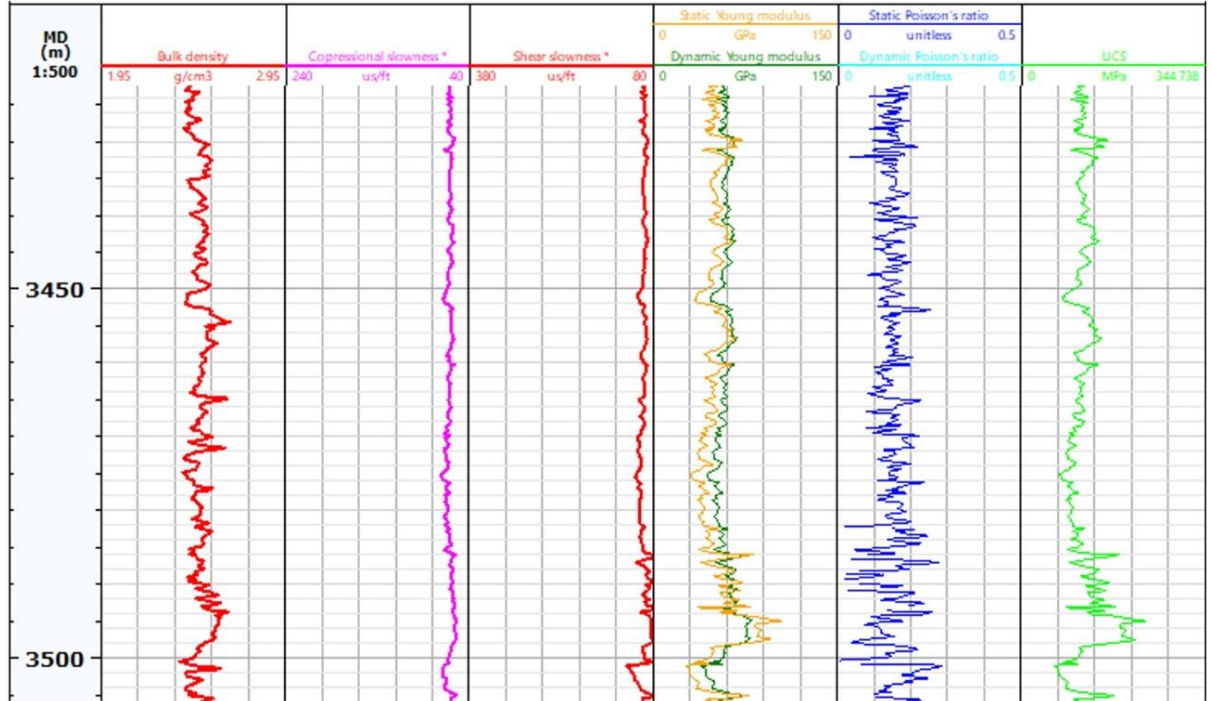


Figure 0-4 Dynamic and static elastic rock properties

III.3.1.5 Rock strength properties

The unconfined compressive strength (UCS) can be defined from the static Young modulus data using the correlation formula below (with $R^2 = 0.9073$). Along the wellbore, a steady UCS pattern took shape from this link.

$$UCS = 2.1595 * E_{stat} + 6.3235 \quad \text{Eq 0-1}$$

So the friction angle along with tensile strength came straight from the UCS log, tied to the gamma ray readings, built step by step across the layer. Each value moved smoothly through the rock zone, shaped by those two logs working together. The method held steady, never breaking pace from top to bottom.

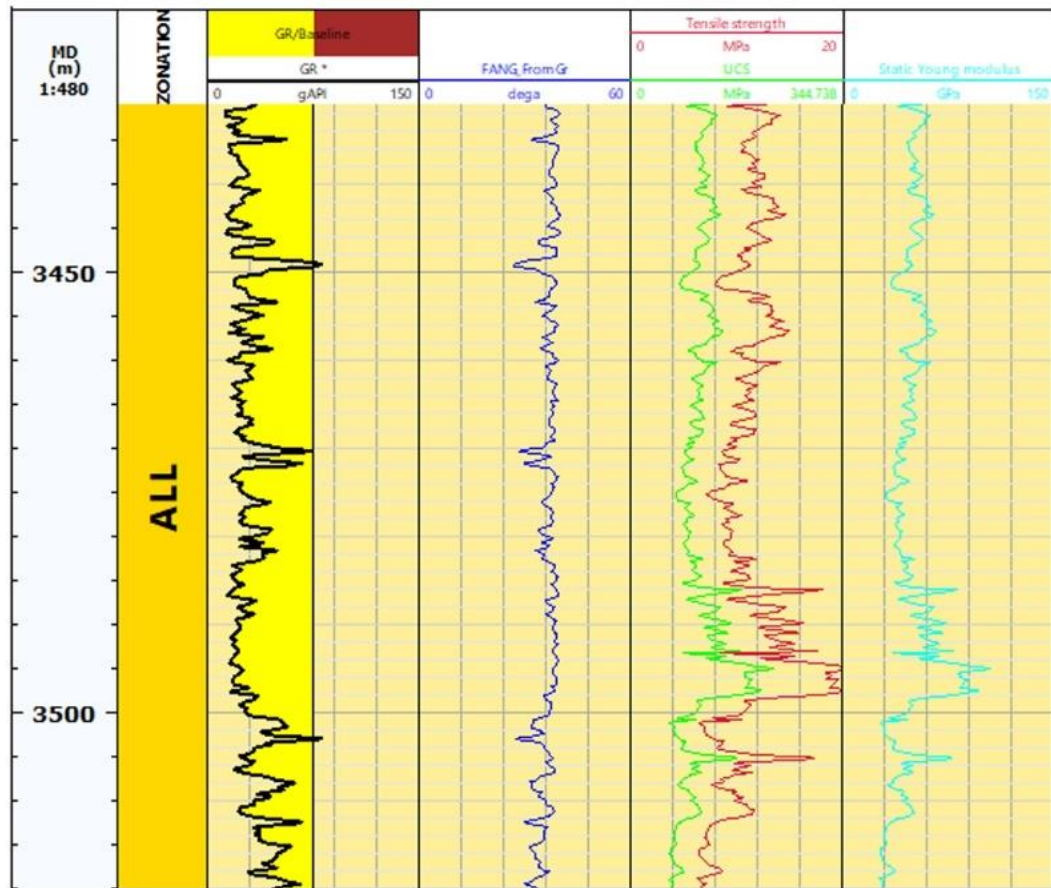


Figure 0-5 Rock strength properties

III.3.1.6 In-situ horizontal stresses

Maximum horizontal stress and minimum horizontal stress are represented by the poroelastic isotropic, ε_{SHmin} and ε_{SHmax} are assumed 0.0003 and 0.0008 respectively. rules.

Starting from these assumptions, the stress calculation took them as inputs to approximate how horizontal stress spreads underground. While built on simplifications, they guided the model’s grasp of real-world pressure patterns across the layer. Each parameter shaped the outcome, influencing the predicted behavior inside the rock unit.

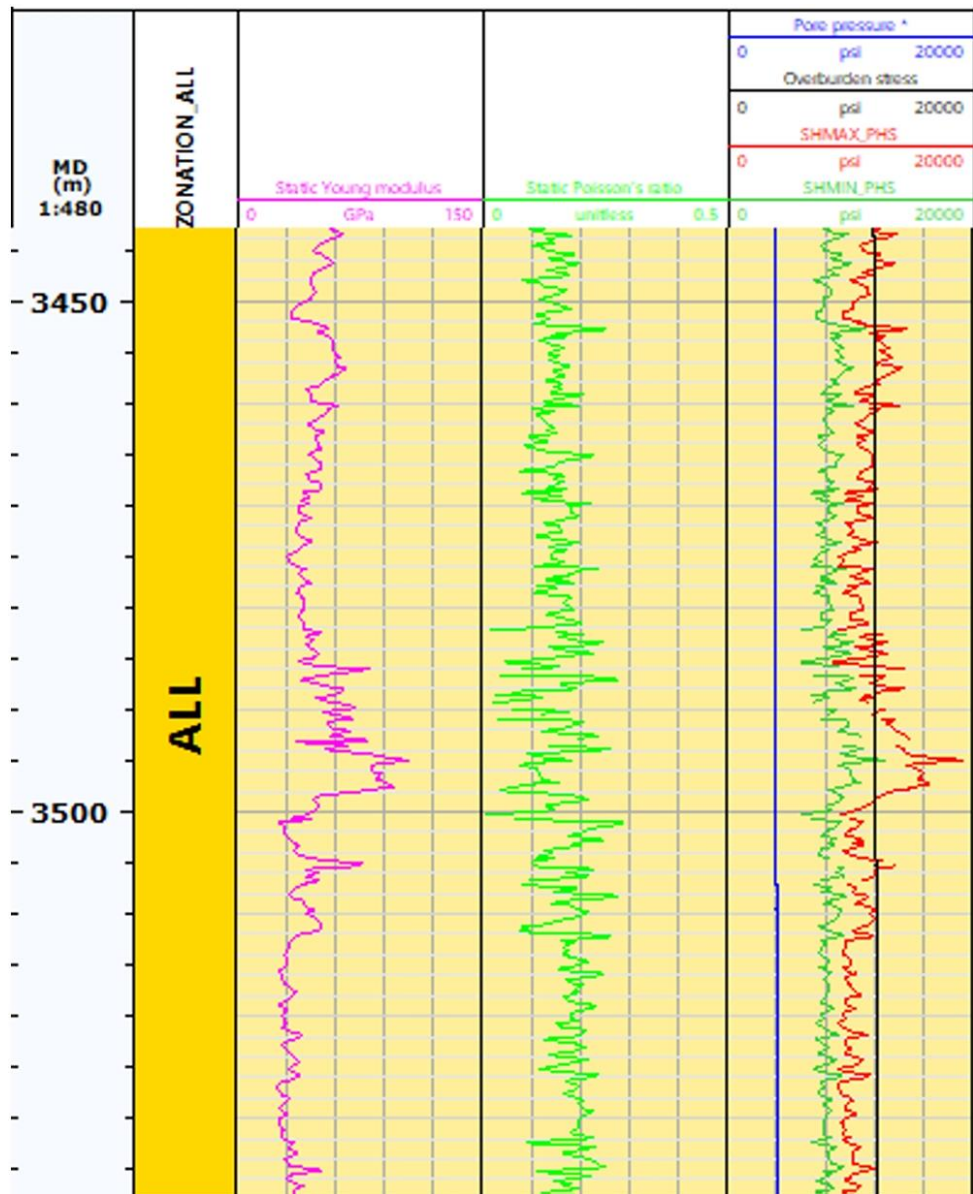


Figure 0-6 Insitu horizontal stresses

III.3.1.7 In-situ stress orientations

Close to one another on the map sit Well-1 and Well-2. Because of matching geological conditions, their in-situ stress direction is thought identical. Structural alignment supports this shared state. Nearby placement suggests common subsurface forces shape both locations.

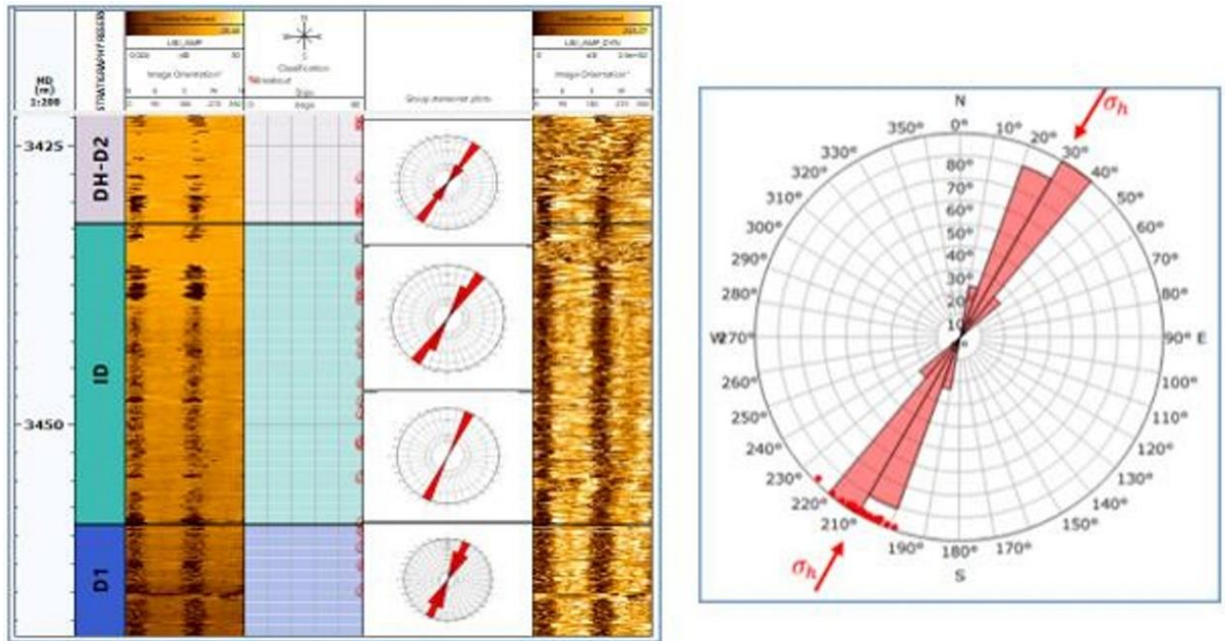


Figure 0-7 In-situ stress orientation of offset well

III.3.1.8 Wellbore stability analysis

A wellbore stability profile emerged from combining the Mohr–Coulomb failure rule with the earlier one-dimensional Mechanical Earth Model, also assuming that the maximum horizontal stress direction is 120 degrees. Drilling fluid density stood at 1.45 specific gravity throughout evaluations. The equivalent circulating pressure reached slightly higher, peaking at 1.47 specific gravity under flow conditions. Starting from these inputs, engineers assessed the shear failure, pore pressure, fracture, and breakdown gradients down the borehole path. Because each factor was analyzed together, the evaluation captured how stable the hole remained during drilling under real underground stresses.

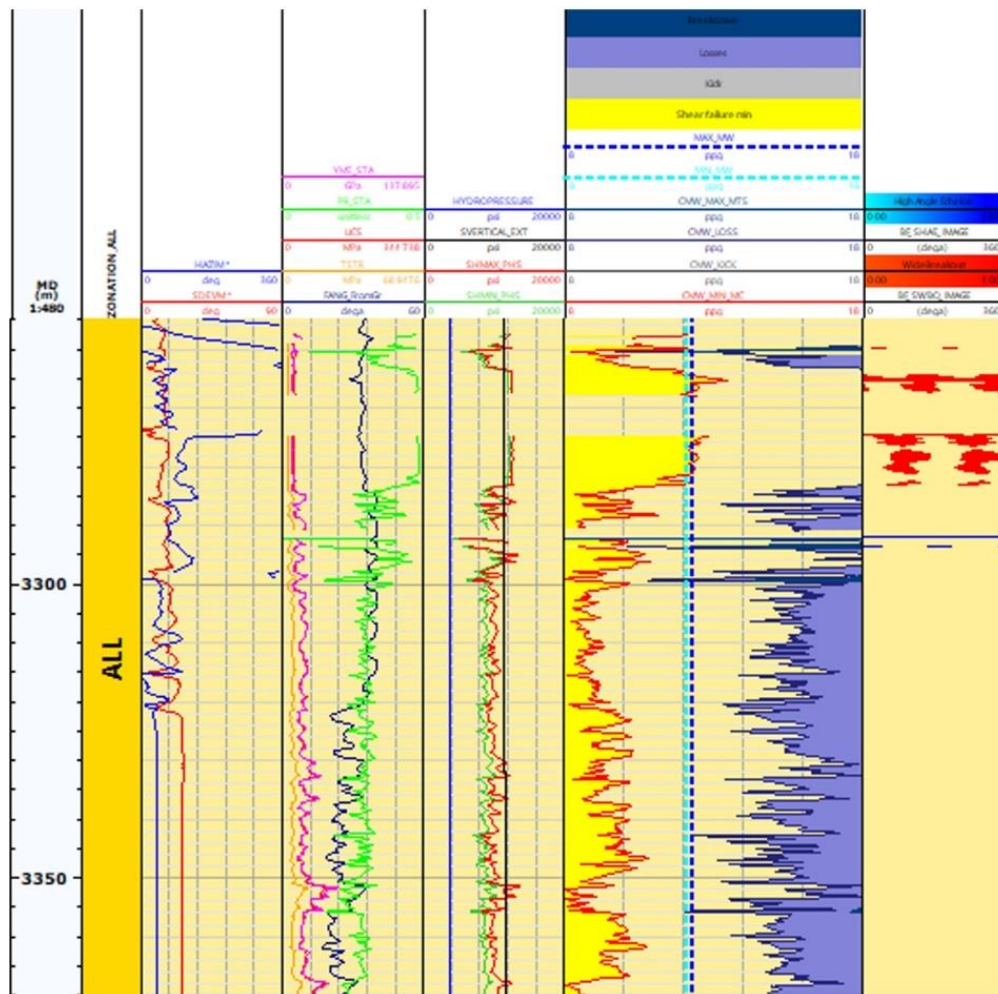


Figure 0-8 Descriptive diagram of the far field and near wellbore stresses on the well

III.3.1.9 Failure and stability discussion

Here, the least horizontal stress lines up close to 30 degrees. Figure illustrations reveal exceeding 3.98 sg (33.2 ppg) risks fracturing the rock at 3440 meters deep. Though safe drilling demands staying under that limit.

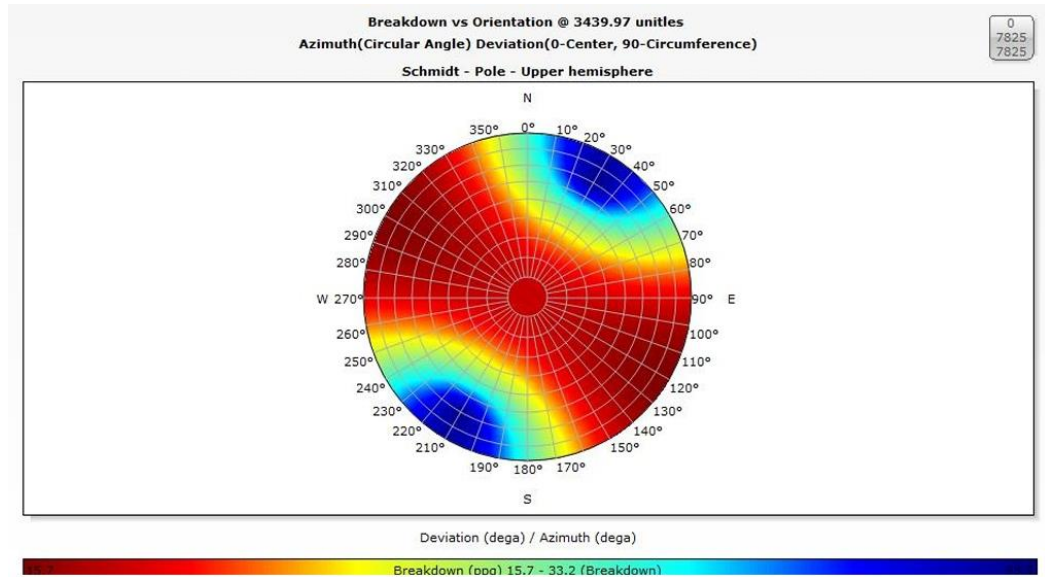


Figure 0-9 Breakdown limits profile

Still, keeping the mud weight below 0.73 sg (6.1 ppg) could lead to shear failure, given that depth and well angle. Instead, maintaining it at or above this level helps avoid structural breakdown under those conditions.

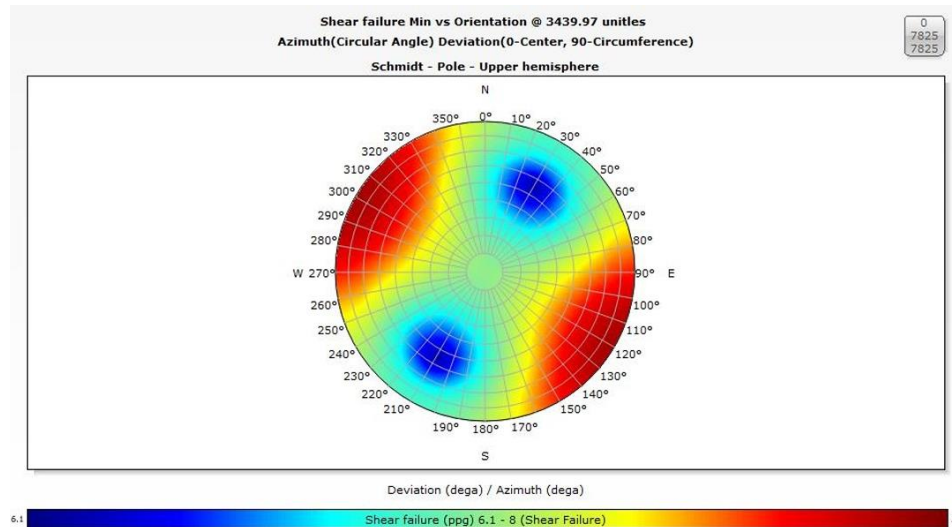


Figure 0-10 Shear failure limits profile

III.3.2 Section II (Horizontal drain)

Starting at the prior endpoint, the horizontal segment advanced until reaching a true vertical depth of 3413.55 meters and a total measured length of 3530 meters. Drilling proceeded with fluid density set to 0.9 specific gravity, holding steady on course - maintaining 90 degrees of tilt and facing roughly 35.18 degrees in compass alignment. Progressing laterally by 217.97 meters, the bore continued within the reservoir zone, ultimately achieving a final measurement of 4375 meters along its path.

Ending its path horizontally, the well achieved a true vertical depth of 3418.82 meters. Its angle measured 88.70 degrees from vertical. Facing 35 degrees in compass direction, it extended underground. Roughly 1060 meters marked its vertical projection. Directional data confirmed alignment across multiple planes.

III.3.2.1 Overburden stress

Because the bulk density log (RHOZ) wasn't available here, the density curve got built from compressional slowness (DTCO). An observed pattern linking these two guided the estimation. From that, a predictive formula emerged - shown next

$$RHOZ = 1.687 * DTC6^{0.0979} \quad \text{Eq 0-2}$$

Where RHOZ is the bulk density and DTCO is the compressional slowness.

Starting from the synthetic bulk density log, the vertical stress profile took shape through extrapolation. A full picture of overburden stress emerged across the whole wellbore. This approach allowed steady estimates without gaps. From that point on, continuity became possible in tracking stress changes down deep.

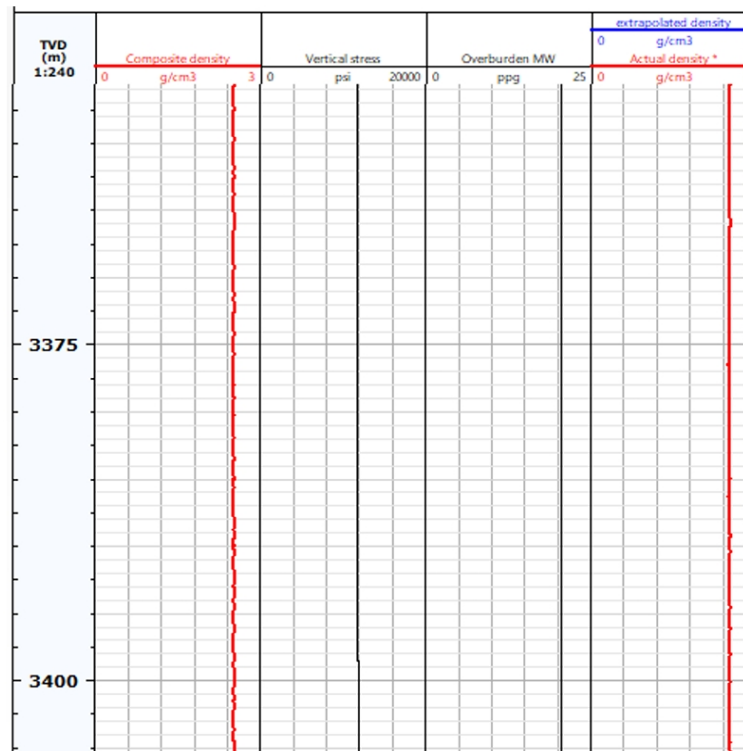


Figure 0-11 Overburden stress of well 2

III.3.2.2 Pore pressure estimation

Assuming a mud weight of 0.9 sg and a pressure gradient of 0.0791 bar/m, the pore pressure was consequently estimated. Based on these input parameters, the calculated pore pressure at the target depth is approximately 300.89 bar.

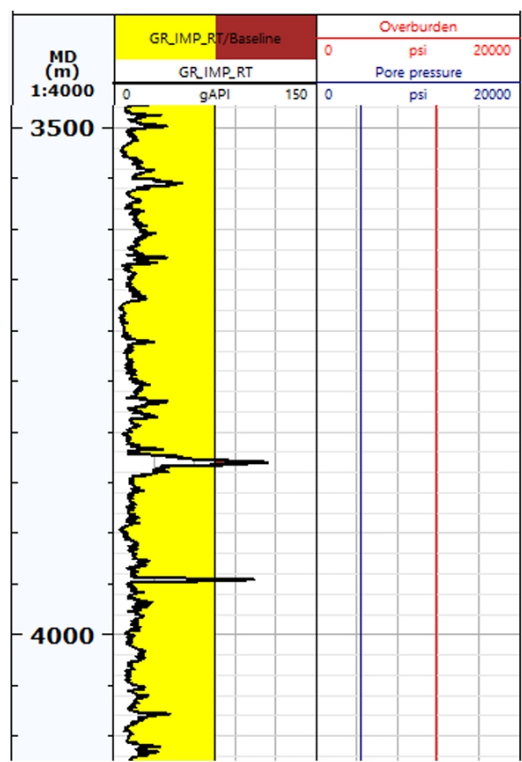


Figure 0-12 Pore pressure estimation of well 2

III.3.2.3 Rock elastic properties

Young’s modulus and Poisson’s ratio came from combining bulk density logs with sonic log results, taken during well logging. Because those inputs link closely to rock behavior under stress, they helped form the basis for calculating how the material stretches and compresses. Earlier details explained how such values are tied directly to wave speeds and density patterns seen underground.

Later on, the shifting traits turned into fixed stiffness values using that earlier link, holding the lively and steady stretchiness in step while matching up log reactions down the borehole.

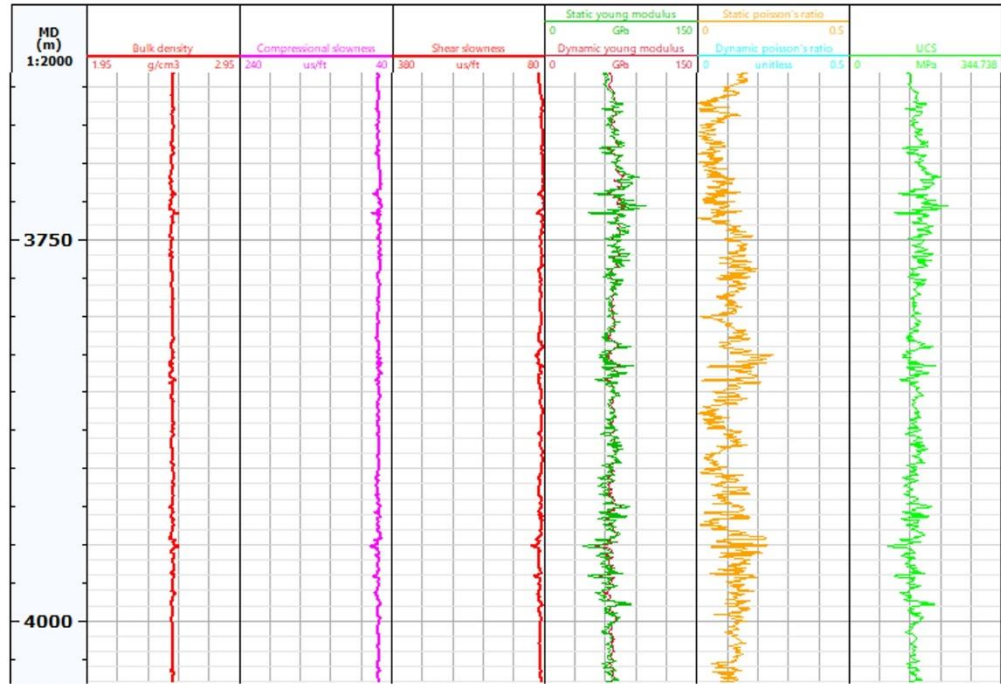


Figure 0-13 Dynamic and static rock elastic properties

III.3.2.4 Rock strength properties

From the static Young's modulus, it's possible to estimate unconfined compressive strength through the earlier regression model. A smooth UCS curve across the borehole follows when that method is applied.

One step further, the UCS log helps uncover more mechanical traits. Especially, knowing the UCS pattern allows an estimate of tensile strength. At the same time, the friction angle comes from the gamma ray (GR) record. Together, these build a full picture of the formation's mechanics.

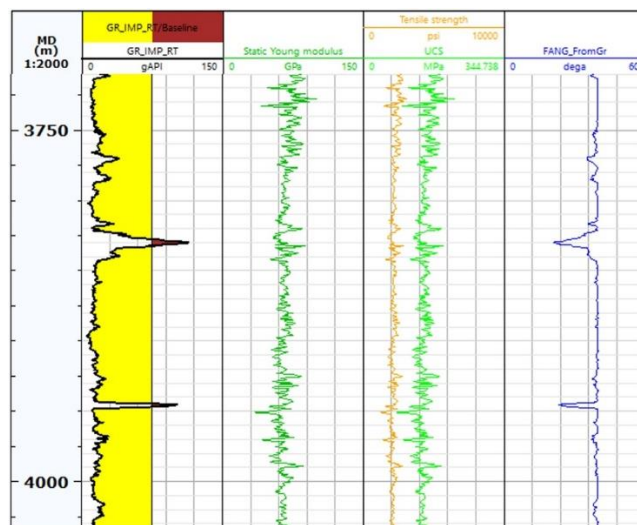


Figure 0-14 Rock strength properties

III.3.2.5 In-situ horizontal stresses

Starting from ϵ_{SHmin} at 0.0003, while also taking into account a Biot's coefficient equal to 1, researchers built a poroelastic model for horizontal strain. Though ϵ_{SHmax} sits higher at 0.0008, the framework still links deformation directly to pore pressure changes. Because both strains feed into the system, the result turns out sensitive to small shifts in stress. Since the coefficient holds steady at one, fluid effects show up more clearly across the model outputs.

From this model came estimates of horizontal stress size. Stress directions were pinned down using its results. The main type of faulting in the rock layer showed up clearly through analysis.

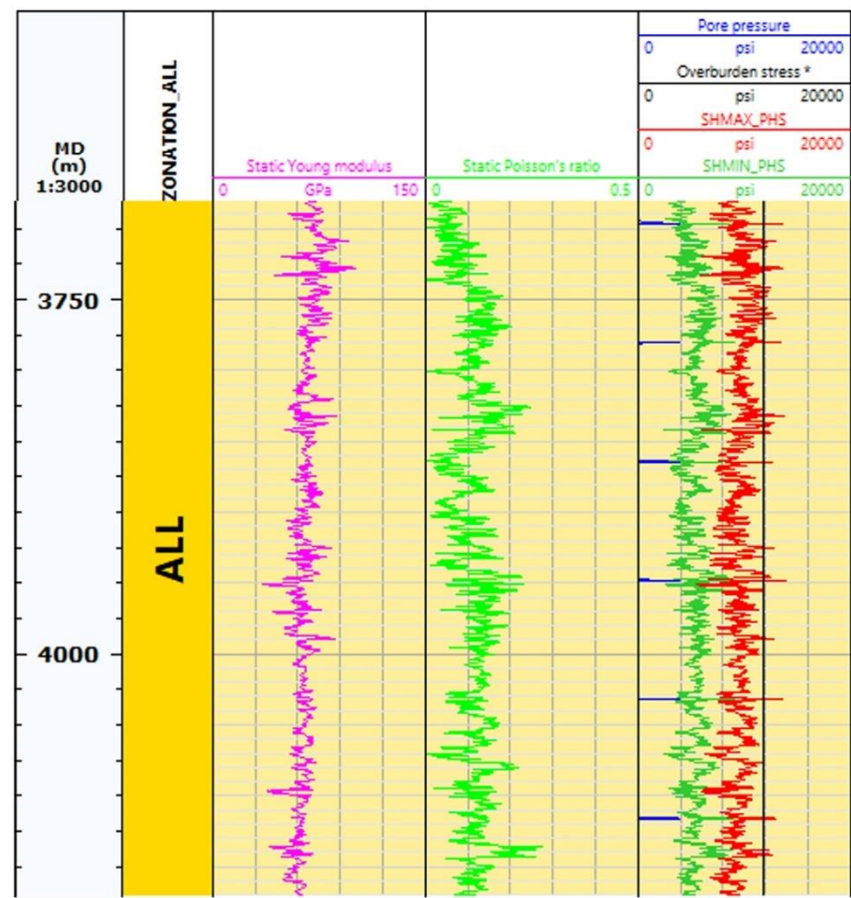


Figure 0-15 Horizontal in-situ stresses

III.3.2.6 Wellbore stability analysis

Once every part of the 1D Mechanical Earth Model is built, the last stage involves checking if the borehole holds up, based on how rock fails under pressure. This check runs with the biggest sideways push lined up at 120 degrees. The fluid used weighs 0.9 specific gravity. While drilling, that mix thickens slightly - reaching 1.44 specific gravity.

From this data, shear failure risk shows up alongside pore pressure clues. The drill path gets checked piece by piece using how rock splits under stress. Breakdown signs appear where forces shift too far. Each step adds context to whether walls hold or slip.

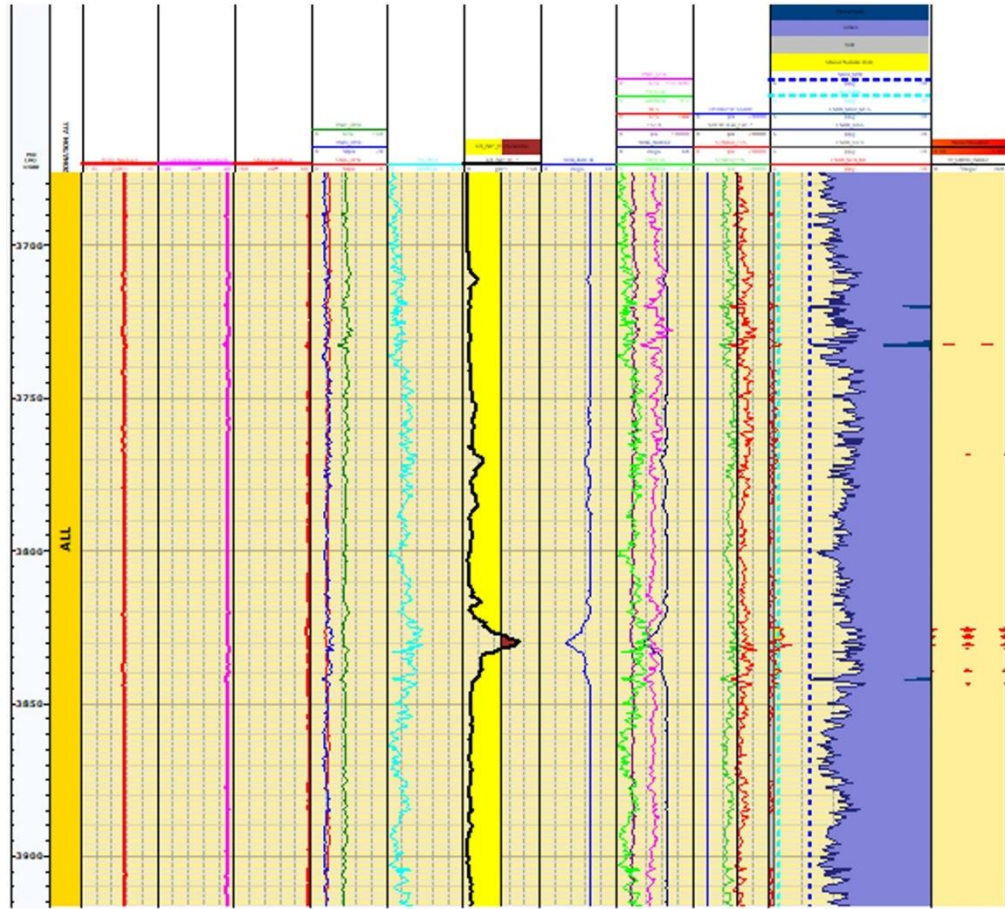


Figure 0-16 Final 1D MEM and wellbore stability modeling

III.3.2.7 Results and discussion

Some results from the model on wellbore stability include the following:

- The first phase of the initial section ranges from the kickoff point at 3100 m up to 3311 m TVD at 3320 m MD. In this range, there is a vertical range of 49.37 m, inclined at an angle of 25° and azimuth of 40°.
- The second phase of the initial section ranges from 3315 m to 3381.97 m TVD and MD of 3412 m. This section contains a vertical range of 107.3 m, inclined at an angle of 49.40° and azimuth of 37.09°.
- There is a horizontal drain starting from 3413.55 m TVD and MD of 3530 m and ranging to 3418.82 m TVD and MD of 4375 m. It is inclined at an angle of 88.70° and azimuth of 35°. The vertical distance is approximately 1060 m.

- The regime of stress along the reservoir section is the strike slip regime, which has the following parameters:
- $\sigma_H > \sigma_v > \sigma_h$
- The fracture gradient along the reservoir section is about 0.0791 bar/m.
- The window for mud weight is between 0.73 sg and 3.98 sg. Higher mud weights than 3.98 sg will cause formation breakdown, while those less than 0.73 sg will induce shear failure.

III.3.2.8 Modelling uncertainties

While constructing the 1D Mechanical Earth Model and conducting the wellbore stability analysis for Well-2, a number of uncertainties and operational difficulties were observed.

- The lack of a bulk density log compromised the accuracy of overburden stress calculations along the well path.
- Pore pressure uncertainty had a notable effect on the determination of both in-situ and near-wellbore stress conditions.
- Static elastic properties were estimated using empirical correlations, introducing further uncertainty and affecting the reliability of derived rock strength values.
- Estimating the magnitude of horizontal in-situ stresses remained uncertain, primarily due to inconsistencies in pore pressure and elastic property assessments. Additionally, formation anisotropy was not accounted for in this analysis, potentially reducing the confidence in the resulting stress estimates.
- The absence of borehole imaging data hindered the identification of wellbore breakouts and the assessment of their orientation, limiting the accuracy of stress direction interpretation.
- On the operational side, drilling the horizontal section faced several issues, such as challenges navigating the build-up section at various depths, partial losses of drilling mud, and incidents of stuck pipe during both drilling and logging runs. These problems led to extended non-productive time and increased overall drilling expenses.

IV. Conclusion

The purpose of this research is to gain insight into petroleum geomechanics and how important it is for maintaining stable wellbores while drilling. The main focus of the research will be to develop a solution for wellbore instability issues (mud losses, stuck pipe, and non-productive time [NPT]) to achieve optimal drilling performance and lower drilling costs. The study concentrates on defining the safe mud weight window as well as providing a means to drill a horizontal drain with an azimuth parallel to the direction of min horizontal stress, focused on stability.

Geomechanics has been established as a useful approach to predicting and preventing Wellbore Instability by creating a 1D MEM of the subsurface; this research shows how the geomechanical approach is effective for predicting and preventing drilling induced instability through use of a structured workflow starting with data collection (drilling reports, core data, and geophysical logs) to create an MEM for offset wells before using the MEM to assess wellbore stability and pre-drill predictions.

Offset well data were integrated to estimate near-wellbore stresses, formation deformation parameters and stability behaviour. This also produced synthetic wellbore image logs that identified regional stress orientations and deformation magnitudes (ϵ_{min} and ϵ_{max}), which were key for selecting the safest drilling trajectory and associated mud window for the pilot and horizontal sections.

The study affirmed that the use of calibrated 1D MEM based on data from offset wells is a good predictor of pre-drill conditions in new wells, particularly where the geological environment is complex like Hassi Messaoud field. This gives a good basis for reducing uncertainty surrounding the pore pressure, in-situ stresses and rock mechanical properties that are typically associated with instability problems.

Some limitations were also identified during the initial study. An assumption of Biot's coefficient equal to 1 was made, but without detailed calibration, an assumption of empirical correlations was given for rock elastic property determinations due to the lack of all laboratory measurements. In addition, the effects of formation anisotropy were not adequately considered, which could lead to uncertainties in the final geomechanical model.

The data collected has limitations, but nonetheless it can be relied upon for sound drilling decisions, as well as enhancement of wellbore stability management.

In future work, the workflow developed can be used to develop an advanced 3-D (three-dimensional) Mechanical Earth Model (MEM), which will improve the accuracy of stress prediction and instability analysis.

This study has demonstrated that including geomechanics in drilling engineering workflow is important. The MEM and stability models produced here can serve as useful tools to help reduce drilling

risks, optimize mud weight selection, improve reservoir characterization, and facilitate hydraulic fracturing designs for future field development efforts. The data collected has limitations, but nonetheless it can be relied upon for sound drilling decisions, as well as enhancement of wellbore stability management.

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