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PETROPHYSICAL AND GEOMECHANICAL MODELLING FOR MUD-WEIGHT WINDOW PREDICTION: A 1D-MEM ANALYSIS OF WELL A IN SOUTH SUMATRA FIELD, INDONESIA

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ABSTRACT

The optimization of drilling operations in increasingly complex geological environments, including conventional and unconventional oil and gas resources, demands geomechanical evaluations to mitigate costly non-productive time. Wellbore instability, primarily driven by inadequate mud weight design, remains a persistent operational challenge that can lead to catastrophic failures such as well collapse, tight hole conditions, and stuck pipe incidents. To address these mechanical risks, a 1-Dimensional Mechanical Earth Model (1D-MEM) provides a comprehensive analytical framework by synthesizing petrophysical measurements with localized stress profiles to determine the mechanical limits of the formation. Utilizing depth records and a suite of acoustic, density, and caliper well logs, this study constructs an integrated 1D-MEM for Well A. The analytical procedure quantifies dynamic elastic moduli and estimates rock strength parameters, specifically the uniaxial compressive strength and internal friction angle, along the wellbore trajectory. By superimposing the predicted in-situ principal stresses with the appropriate rock failure criterias, the study analytically determines the shear and tensile failure gradient. The central finding of this modelling effort establishes the precise mud weight window required to counterbalance the effective principal stresses and prevent wellbore breakouts. Establishing this optimized geomechanical parameter not only ensures operational safety and structural integrity for Well A but also yields a predictive analytical methodology that can be extrapolated to future drilling and well intervention programs within similar lithological settings.

Keywords: *Petrophysical and geomechanical modelling; Mechanical Earth Model; mud weight window; wellbore stability; drilling optimization*

Abstrak

Optimalisasi operasi pengeboran di lingkungan geologi yang semakin kompleks, termasuk sumber daya minyak dan gas konvensional maupun nonkonvensional, menuntut evaluasi geomekanika untuk mengurangi waktu nonproduktif yang mahal. Ketidakstabilan lubang sumur, yang terutama disebabkan oleh desain berat lumpur yang tidak memadai, tetap menjadi tantangan operasional yang berkelanjutan dan dapat menyebabkan kegagalan katastrofik seperti keruntuhan sumur, kondisi lubang ketat, dan insiden pipa terjepit. Untuk mengatasi risiko mekanis tersebut, Model Bumi Mekanis 1-Dimensi (1D-MEM) menyediakan kerangka analitis yang komprehensif dengan menyintesis pengukuran petrofisika dan profil tegangan lokal untuk menentukan batas mekanis formasi. Dengan memanfaatkan rekaman kedalaman serta rangkaian log sumur akustik, densitas, dan kaliper, penelitian ini membangun 1D-MEM terintegrasi untuk Sumur A. Prosedur analitis ini mengkuantifikasi modulus elastis dinamis dan mengestimasi parameter kekuatan batuan, khususnya kuat tekan uniaksial dan sudut gesek internal, di sepanjang lintasan lubang sumur. Dengan menumpangkan tegangan utama in-situ yang diprediksi pada kriteria kegagalan batuan yang sesuai, penelitian ini secara analitis menentukan gradien kegagalan geser dan tarik. Temuan utama dari upaya pemodelan ini menetapkan jendela berat lumpur yang tepat yang diperlukan untuk mengimbangi tegangan utama efektif dan mencegah breakout lubang sumur. Penetapan parameter geomekanika yang dioptimalkan

ini tidak hanya menjamin keselamatan operasional dan integritas struktural Sumur A, tetapi juga menghasilkan metodologi analitis prediktif yang dapat diekstrapolasi ke program pengeboran dan intervensi sumur di masa depan pada kondisi litologi yang serupa.

Kata Kunci: Pemodelan petrofisika dan geomekanika; Model Bumi Mekanis; jendela berat lumpur; stabilitas lubang sumur; optimalisasi pengeboran.

1. INTRODUCTION

Drilling through complex subsurface formations requires the precise management of geomechanical stresses to ensure wellbore integrity and operational efficiency. In the petroleum industry, wellbore instability remains one of the most significant and costly challenges, frequently leading to severe drilling complications such as tight holes, pipe sticking, severe washouts, and lost circulation. These geomechanical hazards are primary contributors to Non-Productive Time (NPT) and escalate overall well construction costs. To mitigate these risks, optimizing the mud weight window is a critical operational priority. The drilling fluid density must be maintained within a strict geomechanical boundary: it must be sufficiently high to provide hydrostatic support against shear failure (wellbore breakouts) and formation fluid influx, yet adequately low to prevent exceeding the formation's tensile strength, which would induce tensile fractures and subsequent drilling fluid losses.

Despite the well-established theoretical foundations of petroleum rock mechanics, a significant analytical gap persists in the dynamic application of these principles to specific, structurally complex local fields. Historically, many drilling programs have relied on generalized, regional stress models or offset well data that lack the high-resolution, depth-specific precision required for highly variable lithologies. Furthermore, conventional predictive models often fail to dynamically integrate real-time acoustic and density log responses with physical wellbore failure evidence, leading to suboptimal or overly conservative mud weight windows. This discrepancy between generalized regional stress assumptions and the actual localized geomechanical realities of a specific reservoir, such as those encountered in the field, restricts the ability of drilling engineers to make precise, real-time fluid density adjustments, particularly when navigating through zones with abnormal pore pressure or reactive shale intervals.

To address this critical gap, this study systematically applies a comprehensive One-Dimensional Mechanical Earth Model (1D-MEM) tailored specifically to Well A. By dynamically synthesizing depth-matched sonic acoustic logs, density logs, and actual pressure test data (pore and fracture pressures), this research constructs a high-resolution, continuous profile of the subsurface stress regime and rock elastic properties. Furthermore, the caliper log is screened for borehole enlargement as a qualitative field check of the predicted wellbore stability response. The resulting analysis provides a site-specific analytical framework to support future drilling safety and performance.

(1) Objectives

1. To construct a continuous, high-resolution One-Dimensional Mechanical Earth Model (1D-MEM) for Well A by integrating density and sonic acoustic logs to determine dynamic rock elastic properties.
2. To quantify the dynamic rock mechanical properties and analytically determine the prevailing in-situ stress profiles (vertical, maximum, and minimum horizontal stresses) within the target formation.
3. To evaluate the potential for wellbore shear and tensile failure by applying the appropriate failure criteria along the planned wellbore trajectory.
4. To predict the optimum mud weight required to prevent wellbore breakouts and ensure long-term structural stability during drilling and well intervention operations.

2. LITERATURE REVIEW

2.1. In-Situ Stresses and Pore Pressure

Stress is defined by the force divided by the area. On a real or imaginary plane through a rock, there can be normal force (ΔN) and shear force (ΔS). The forces induce normal and shear stresses in the rock, whereas solids can sustain shear force and shear stress unlike gases or liquids. A liquid or gas contains a pressure, i.e., a force per unit area which acts equally in all directions and hence is a scalar quantity. However, stresses in rocks are not normally equal in different directions, hence they are vectors. The normal and shear stresses can be mathematically defined as follows when the size of the small area is reduced to zero.

$$\sigma_n = \lim_{\Delta A \rightarrow 0} \frac{\Delta N}{\Delta A} \quad (1)$$

$$\tau = \lim_{\Delta A \rightarrow 0} \frac{\Delta S}{\Delta A} \quad (2)$$

Where σ_n is normal stress and τ is the shear stress.

For any given state of stress at a specific point within a rock mass, there exists a unique coordinate system comprising three mutually orthogonal axes where all shear stress components evaluate to zero. The planes oriented perpendicular to these axes are defined as the principal planes, and the normal stresses acting directly upon them attain their absolute extreme magnitudes. These orthogonal forces are designated as the principal stresses, typically denoted as the maximum (σ_1), intermediate (σ_2), and minimum (σ_3) principal stresses. Consequently, when the reference coordinate system is aligned with these principal axes, the general stress tensor is diagonalized and can be mathematically expressed strictly in terms of its three principal stress components as follows:

$$\sigma = \begin{pmatrix} \sigma_x & 0 & 0 \\ 0 & \sigma_y & 0 \\ 0 & 0 & \sigma_z \end{pmatrix} \quad (3)$$

In-situ stress state is the original stress status in the rock before excavations or other perturbations. In situ stresses are also called far-field stresses. Generally, in situ stresses include three mutually orthogonal principal stresses in the subsurface, which can be defined as the vertical (overburden) stress and the maximum and minimum horizontal stresses ($\sigma_v, \sigma_h, \sigma_h$). Three in situ stresses correspond to three principal stresses, namely the greatest stress (σ_1), the intermediate stress (σ_2), and the least stress (σ_3). According to the relationship of these three principal stresses, three in situ stress regimes can be used to describe in situ stress states based on the faulting theory by Anderson (1951). Assuming that the faults were formed by shear failures caused by in situ stresses, the following three stress regimes can be classified based on the relationship of shear failures and principal stresses:

- a. Normal faulting stress regime. The vertical stress drives normal faulting (shear failure), and the shear slip occurs to form the normal fault when the minimum stress reaches a sufficiently low value.

$$\sigma_v \geq \sigma_H \geq \sigma_h \quad (4)$$

- b. Strike-slip faulting stress regime. The vertical stress is the intermediate principal stress, and the maximum horizontal stress causes faulting (shear failure).

$$\sigma_H \geq \sigma_v \geq \sigma_h \quad (5)$$

- c. Reverse or thrust faulting stress regime. The vertical stress is the least principal stress, the maximum horizontal stress causes thrust faulting (shear failure).

$$\sigma_H \geq \sigma_h \geq \sigma_v \quad (6)$$

The concept of effective stress that [60] proposed has been widely used to investigate the effect of pore pressure on the mechanical properties of saturated rocks. Effective stress is the applied stress, or total stress, minus the product of fluid pressure (the pore pressure) and effective stress coefficient, which can be expressed as:

$$\sigma' = \sigma - \alpha p_p \quad (7)$$

Where σ and σ' are the total and effective stress, respectively, p_p is the pore pressure, and α is Biot's coefficient (1941).

(1) Vertical stress

Vertical stress or overburden stress is caused by the weight of the overlying formations. If the overlying formations have bulk densities of rocks that vary with depth, the vertical stress can be calculated by the integration of the densities to the depth of interest, Z , i.e.,

$$\sigma_V = g \int_0^Z \rho_b(z) dz \quad (8)$$

Where ρ_b is the formation bulk density as a function of depth and can be obtained from density log.

(2) Horizontal Stresses

In the normal faulting stress regime, the minimum horizontal stress is the minimum principal stress and can be calculated by assuming the uniaxial strain condition. For poroelastic formations, the minimum and maximum horizontal stress can be expressed using the poroelastic horizontal strain model (Fjaer et al., 2008) in the following:

$$\sigma_h = \frac{v}{1-v} \sigma_V + \frac{1-2v}{1-v} \alpha p_p + \frac{E}{1-v^2} \epsilon_x + \frac{vE}{1-v^2} \epsilon_y \quad (9)$$

The maximum horizontal stress σ_H can be obtained from the following equation:

$$\sigma_H = \frac{v}{1-v} \sigma_V + \frac{1-2v}{1-v} \alpha p_p + \frac{E}{1-v^2} \epsilon_y + \frac{vE}{1-v^2} \epsilon_x \quad (10)$$

Where σ_V is the vertical stress, v is the Poisson's ratio, p_p is the pore pressure, α is the Biot's coefficient, E is the static Young's modulus, and ϵ_x and ϵ_y are the tectonic strains in maximum and minimum horizontal stress direction, respectively. These two parameters were obtained by using the following equations:

$$\epsilon_x = \frac{\sigma_V v}{E_s} \left(\frac{1}{1-v} - 1 \right) \quad (11)$$

$$\epsilon_y = \frac{\sigma_V v}{E_s} \left(1 - \frac{v^2}{1-v} \right) \quad (12)$$

2.2. Petrophysical and Geomechanical Properties

(3) Porosity and Neutron Density Cross Plots

Porosity is the ration of fluid volume in a porous medium to the total volume of that medium (Alyafei, 2021). In the context of core analysis, effective porosity is the porosity measured after being dried at 100°C or more, in which case it is considered that all the clay bound water is removed.

The determination of porosity can be executed by deploying the data obtained from logging measurements, specifically density log, neutron log, and sonic log [41].

Frequently, a combination of porosity devices can be run into the wellbore together. In many cases, these combination of tools can define porosity better than any single porosity device by itself. The most commonly available pair is the neutron density combination. Regardless of the lithology, the determination of porosity using the previously mentioned combination can be done in the following manner [7].

$$\bar{\phi} = \frac{\phi_D + \phi_N}{2} \quad (13)$$

The porosity derived from the acoustic (sonic) log better represents primary porosity of the formation.

(4) Sonic velocities and transit time

When a seismic or sonic wave propagates in rock formation, the two major wave types available are the compressional wave and shear wave. The propagation velocities are determined by the appropriate elastic moduli and densities of the materials that the waves pass through. Therefore, rock properties and pore pressure can be estimated from seismic interval velocities and the travel time in sonic log. Compressional body waves propagate by alternating compression and dilation in the direction of the waves. The compressional velocity (V_p) and dynamic elastic moduli have the following relations:

$$V_p = \sqrt{\frac{K_d + \left(\frac{4}{3}\right)\mu_d}{\rho_b}} \quad (14)$$

$$V_p = \sqrt{\frac{E_d(1 - \nu_d)}{\rho_b(1 + \nu_d)(1 - 2\nu_d)}} \quad (15)$$

Where K_d is the dynamic bulk modulus, μ_d is the dynamic shear modulus, E_d is the dynamic Young's modulus, ν_d is the dynamic Poisson's ratio.

Shear body waves propagate by a sinusoidal pure shear strain in a direction perpendicular to the direction of the waves. Therefore, dynamic shear modulus controls the shear velocity of propagation:

$$V_s = \sqrt{\frac{\mu_d}{\rho_b}} = \sqrt{\frac{E_d}{\rho_b} \frac{1}{2(1 + \nu_d)}} \quad (16)$$

For a fluid the shear modulus is zero, hence the shear wave velocity is zero. Therefore, the shear wave is unable to travel through a fluid.

In well log measurements, the sonic transit time is used to represent the acoustic wave velocity. The compressional transit time is the reciprocal of the compressional velocity and has the following form in the imperial unit:

$$\Delta t_p = \frac{10^6}{V_p} \quad (17)$$

Where Δt_p is the compressional transit time of the formation in $\mu\text{s}/\text{ft}$, V_p is the compressional velocity in ft/s .

For a gas-bearing formation, V_p is slowed down by gas, and the relations of V_p and V_s can be used to correct the measured V_p . The ratio of compressional to shear wave velocity (V_p/V_s) depends on the dynamic Poisson's ratio (ν_d) according to the following theoretical equation:

$$\frac{V_p}{V_s} = \sqrt{\frac{2(1 - \nu_d)}{1 - 2\nu_d}} \quad (18)$$

Based on in-situ sonic and field seismic measurements in mud rocks, the relationship of V_p and V_s for sandstones can be estimated using the Han (1986) correlation:

$$V_s = 0.79V_p - 0.79 \quad (19)$$

Where the velocities are in km/s.

(5) Young's Modulus

Young's modulus is one of the important parameters to define the relationship between stress and strain in a material in the linear-elastic deformation. The static Young's modulus can be obtained from laboratory core tests, e.g., uniaxial or triaxial compression test. The dynamic Young's modulus can be calculated from theoretical equations using the acoustic velocity data.

$$E_d = \rho_b V_p^2 \frac{(1 + \nu_d)(1 - 2\nu_d)}{(1 - \nu_d)} \quad (20)$$

The static axial Young's modulus (E_s) in the laboratory core test is defined as the ratio of the axial stress change ($\Delta\sigma$) to the axial strain change ($\Delta\varepsilon$) produced by the stress change, i.e.,

$$E_s = \frac{\Delta\sigma}{\Delta\varepsilon} \quad (21)$$

Young's modulus describes the capacity of rock deformation. A rock with a high Young's modulus is less deformable.

(6) Poisson's Ratio

Poisson's ratio is the ratio of transverse strain to corresponding axial strain on a material stressed along one axis. For a rock core subjected to an axial load, Poisson's ratio (ν) can be expressed in the following:

$$\nu = -\frac{\varepsilon_l}{\varepsilon_a} \quad (22)$$

Where ε_l and ε_a are the lateral and axial strains, respectively. Therefore, static Poisson's ratio can be determined by measuring the lateral and axial deformations of the uniaxial compression test in the rock sample.

Dynamic Poisson's ratio can be calculated from the compressional and shear velocities of the elastic wave (V_p, V_s), i.e.:

$$\nu_d = \frac{\frac{1}{2} \left(\frac{V_p}{V_s} \right)^2 - 1}{\left(\frac{V_p}{V_s} \right)^2 - 1} \quad (23)$$

(7) Biot's effective stress coefficient

For a porous rock under stress, the solid and fluid parts are deformed independently. Therefore, pore pressure and effective stress need to be considered in a fluid-saturated medium. The effective stress is dependent on the total stress, pore pressure, and Biot's coefficient.

Biot's coefficient is defined as the ratio of static pore space deformation to total bulk-volume change. When the frame bulk modulus or the dry bulk modulus of the porous rock (K_{dry}) and the matrix bulk modulus (K_m) are available, the equation is restated by [49] in the following:

$$\alpha = 1 - \frac{K_{dry}}{K_m} \quad (24)$$

The upper limit of Biot's coefficient is 1. For unconsolidated or high porosity rocks, Biot's coefficient is close to 1.

If no measured Biot's coefficient is available, the empirical equations can be used to estimate Biot's coefficient. The general form of empirical equation of Biot's coefficient given by [35]:

$$\alpha = 1 - (1 - \phi)^{\frac{3}{1-\phi}} \quad (25)$$

Where ϕ is porosity in fractions.

(8) Rock strengths

For evaluating wellbore stability and sand production, rock strength is one of the most important parameters.

The correlations can be obtained using compressional wave velocity (V_p), or equivalently, interval transit time ($\Delta t = \frac{1}{v_p}$), which were directly measured from sonic logs to relate to laboratory-measured rock strengths.

$$c = \frac{5(V_p - 1)}{\sqrt{V_p}} \quad (26)$$

$$\sin \varphi = \frac{V_p - 1}{V_p + 1} \quad (27)$$

Based on the preceding equations, the uniaxial compressive strength (UCS) can be obtained:

$$UCS = 10(V_p - 1) \quad (28)$$

Where the cohesion (c) and the uniaxial compressive strength (UCS) are in MPa, the angle of internal friction (φ) is in degrees, the compressional sonic velocity (V_p) is in km/s, and the transit time (Δt) is in $\mu s/ft$.

2.3. 1-Dimensional Mechanical Earth Model

A Mechanical Earth Model (MEM) is an integrated numerical representation that combines measurement data and modelling to describe the mechanical properties of rocks, in-situ stress conditions, pore pressure, and temperature at a specific depth within the subsurface. This model essentially serves as a data repository that unifies all geomechanical information of a field or basin into a coherent framework. By integrating this information, the MEM can provide insights into the mechanical behavior of rock formations and their response to changes in environmental conditions, such as those induced by the drilling process.

In practice, MEMs can be constructed at various scales, ranging from three-dimensional (3D), two-dimensional (2D) models at the field scale, to one-dimensional (1D) models specific to a wellbore trajectory. A 1D Mechanical Earth Model is constructed along the wellbore based on log data, core data, and local geological information. The construction process generally consists of two main steps. The first step is to build a profile of dynamic and static rock mechanical properties, such as Young's modulus, Poisson's ratio, cohesion, and the internal friction angle, which are derived from petrophysical logs such as density logs, compressional sonic logs, and shear sonic logs. The second step is to quantify the magnitudes of the three principal in-situ stresses (vertical stress, maximum and minimum horizontal stress) and pore pressure as a function of depth.

By integrating all these elements, the 1D Mechanical Earth Model becomes the foundation for analyzing various rock mechanics phenomena around the borehole. This model enables investigation of the wellbore stability and prediction of mud weight window for drilling operation.

2.4. Rock Failure Mechanics and the Mohr Coulomb Failure Criterion

A rock fails when the surrounding stress exceeds its tensile, compressive, or shear strength, whichever is reached first. There are several failure types depending on rock lithology, rock microstructures, and applied stresses.

Significantly, with a moderate amount of confining pressures, the rock failure is characterized by a single plane of fracture, inclined at an angle of less than 45 degrees to the direction of σ_1 . This is a typical shear failure under compressive stresses, and a shear displacement along the surface of the shear fracture is gradient.

Shear failure occurs when the shear strength of a formation is exceeded. When a rock is loaded by the far-field principal stresses, shear stresses can be generated on an inclined plane. Shear failures will occur in the rock when shear stress overcomes the friction stress ($\mu\sigma_n$ or $\sigma_n \tan \varphi$) plus rock inherent shear strength or cohesion (c). The Mohr-Coulomb failure criterion uses this principle to describe shear failure mechanisms.

For dry rocks, the Mohr-Coulomb failure criterion says that when the shear stress, τ , is greater than $c + \sigma_n \tan \varphi$ the shear failure occurs. The Mohr-Coulomb criterion can be written as the following linear form between shear and normal stresses.

$$\tau = c + \sigma_n \tan \varphi \quad (29)$$

Where σ_n is the normal stress, τ is the shear stress, c is the cohesion or the inherent shear strength, φ is the angle of internal friction, $\mu = \tan \varphi$, μ is the coefficient of friction. For a fractured rock, it can be assumed that $c = 0$.

In the principal stress space, $(\sigma_1, \sigma_2, \sigma_3)$, the Mohr-Coulomb failure criterion can be expressed as follows:

$$\sigma_1 = UCS + q\sigma_3 \quad (30)$$

Where σ_1 and σ_3 are the maximum and minimum principal stresses, respectively, and

$$q = \frac{1 + \sin \varphi}{1 - \sin \varphi} \quad (31)$$

Based on the Mohr-Coulomb failure criterion, the UCS, angle of internal friction and cohesion have the following relationship

$$UCS = \frac{2c \cos \varphi}{1 - \sin \varphi} \quad (32)$$

2.5. Wellbore Stability and Mud Weight Window

Wellbore instability is a major cause of wellbore failures and represents a serious challenge in the drilling industry. A lack of accurate wellbore stability analysis brings many problems, such as washouts, breakouts, collapses, peak-offs, struck drill pipes and drill bits, and losses.

Wellbore instabilities are the primary cause of drilling difficulties, make logging very difficult to perform and interpret, add to nonproductive time (NPT), increase costs, and sometimes lead to abandoning the well before it reaches its target. The relationship between mud weight and wellbore failures demonstrates that when the mud weight is less than the pore pressure, the wellbore has splintering failures or washouts. When the mud weight is less than the shear failure gradient, wellbore instability can result in breakouts or hole closure in case of compressive and shear failures. If applied mud weight is higher than the fracture gradient, drilling-induced hydraulic fractures are generated, causing drilling mud losses or even lost circulation. Therefore, to maintain wellbore stability, the applied mud weight should be in an appropriate range.

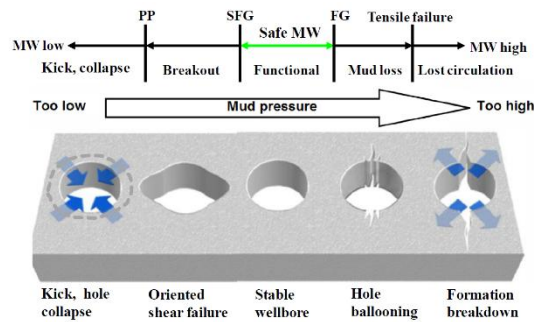


Figure 1. Wellbore stability conditions and failure modes based on mud weight window

Wellbore failures can primarily be classified into the following four categories:

- Wellbore washouts or kicks due to underbalanced drilling, where the downhole mud weight is less than the pore pressure gradient
- Wellbore breakouts or shear failures caused by the induced stress concentrations because the downhole mud weight is lower than the required mud weight.
- Mud losses or lost circulation due to tensile failure caused by higher mud weight than the fracture gradient and tensile failure gradient.
- Rock failures or sliding related to preexisting fractures

3. METHODOLOGY

3.1. Literature Study

This research employs a systematic literature review to establish the foundational theoretical frameworks governing petroleum geomechanics, acoustic log interpretation, and wellbore stability mechanics. Key academic texts, peer-reviewed journals, and industry-standard guidelines concerning the construction of Mechanical Earth Models (MEM) and the mathematical derivation of the Mohr-Coulomb failure criterion were thoroughly evaluated. This theoretical synthesis ensures that the empirical correlations and elastodynamic equations selected for converting raw acoustic and density logs into dynamic rock properties are highly applicable to the specific lithological and structural characteristics of Field Z.

3.2. Data Acquisition

A quantitative, deterministic data collection strategy was executed, utilizing proprietary digital databases provided by the operator of Field Z in South Sumatra. The well log dataset extracted for Well A encompasses continuous, depth-indexed measurements, strictly including depth records, neutron porosity logs, resistivity logs, sonic (acoustic) logs, density logs, and caliper logs. This comprehensive data collection ensured that all necessary inputs were available for analysis.

3.3. Data Preparation

The systematic preparation was executed by extracting raw digital well log records from Log ASCII Standard (LAS) files. To evaluate dataset integrity prior to mathematical computation, continuous depth-indexed measurements specifically Caliper, Bit Size, Gamma Ray, Acoustic Sonic, Thermal Neutron Porosity, and Bulk Density are imported and concurrently visualized into a comprehensive log charts. This acts as an essential quality control mechanism to directly identify petrophysical anomalies and signal attenuation, thereby establishing a reliable lithological and mechanical baseline for the subsequent 1D-MEM calculations.

3.4. Data Analysis

The construction of the One-Dimensional Mechanical Earth Model (1D-MEM) and the subsequent optimization of the mud weight window follow a deterministic, sequential mathematical workflow. The analysis is conducted by rendering well log measurements into a continuous geomechanical profile using the following approaches:

(1) Calculation of Dynamic Poisson's Ratio

The dynamic Poisson's ratio can be calculated from the compressional and shear wave velocities of the elastic wave (V_p, V_s). The velocity of compressional wave is first calculated from the acoustic sonic log which records the transit time of named wave (Δt_p).

$$V_p = \frac{10^6}{\Delta t_p} \times 0.0003048 \quad (33)$$

Where V_p is the compressional wave velocity in km/s and Δt_p is the compressional transit time of the formation in $\mu s/ft$.

For sandstones, the velocity of shear wave can be calculated from the estimation of the relationship of V_p and V_s using the Han (1986) correlation:

$$V_s = 0.79V_p - 0.79 \quad (34)$$

Where the velocities are in km/s.

Subsequently, the dynamic Poisson's ratio (v_d) is calculated using the following equation:

$$v_d = \frac{\frac{1}{2} \left(\frac{V_p}{V_s} \right)^2 - 1}{\left(\frac{V_p}{V_s} \right)^2 - 1} \quad (35)$$

(2) Estimation of Young's Modulus

From well log data, the dynamic Young's modulus (E_d) can be solved from the theoretical equation by knowing the elastic compressional and shear wave velocities of the rock:

$$E_d = \rho_b V_p^2 \frac{(1 + v_d)(1 - 2v_d)}{(1 - v_d)} \quad (36)$$

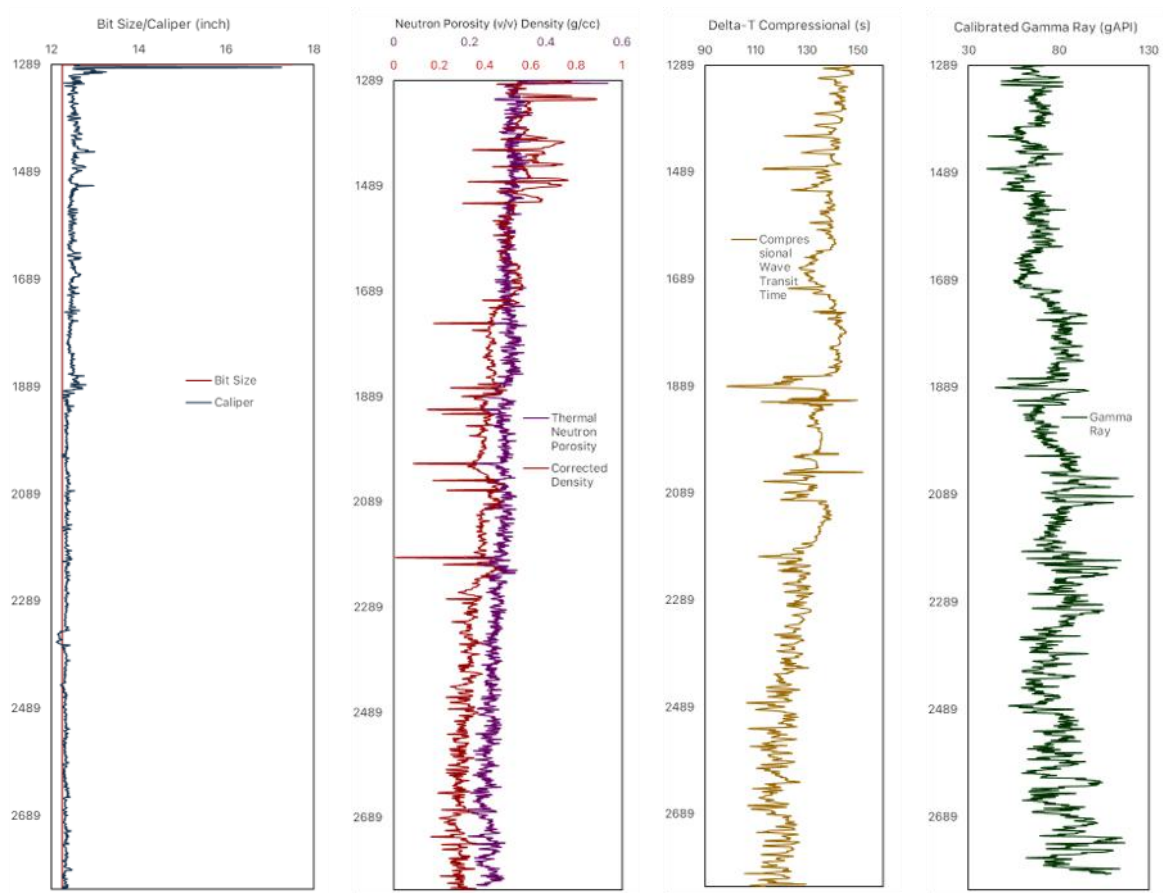


Figure 2.

Where ρ_b is the bulk density, V_p is the compressional velocity, and ν_d is the dynamic Poisson's ratio.

Based on the study by Panchal et al. (2024), the static Young's modulus (E_s) for coarse-grained sandstone can be estimated using the empirical correlation in the following:

$$E_s = 0.8186E_d \quad (37)$$

(3) Estimation of Vertical Stress

The vertical principal stress (σ_v), or overburden stress, represents the pressure exerted by the overlying weight of the rock matrix and interstitial fluids. It is calculated by integrating the bulk density log from the surface to the vertical depth (z) of interest.

$$\sigma_v = \rho_0 g z_o + g \int_0^z \rho_b(z) dz \quad (38)$$

Where ρ_b is the bulk density in g/cm^3 and z is the depth in m .

For bulk datasets, numerical integration using the Simpson's Rule is applied to approximate numerical value of the bulk density.

$$\int_0^z \rho_b(z) dz \approx \frac{3h}{8} [\rho_b(z_0) + 3 \sum_{\text{odd } i} \rho_b(z_i) + 3 \sum_{\text{even } i} \rho_b(z_i) + 2 \sum_{\text{others}} \rho_b(z_i) + \rho_b(z_n)] \quad (39)$$

(4) Estimation of Biot's Effective Stress Coefficient

To estimate the Biot's effective stress coefficient, the true effective porosity of the formation needs to be estimated first hand. The value of corrected porosity (ϕ_{corr}) can be obtained from the corrected Neutron Porosity (ϕ_{Ncorr}) and the corrected Density Porosity (ϕ_{Dcorr}) derived from the bulk density log using arithmetic averaging:

$$\phi_{corr} = \frac{\phi_{Ncorr} + \phi_{Dcorr}}{2} \quad (40)$$

The Biot's effective stress coefficient can be estimated using the following form of generalized empirical equation proposed by [35]:

$$\alpha = 1 - (1 - \phi_{corr})^{\frac{3}{1-\phi}} \quad (41)$$

(5) Estimation of Vertical Stress

The minimum and maximum horizontal stresses (σ_h, σ_H) can be calculated by using the poroelastic horizontal stress model equations by Kidami and Kumar (2016) in the following:

$$\sigma_h = \frac{v}{1-v} \sigma_v + \frac{1-2v}{1-v} \alpha p_p + \frac{E}{1-v^2} \varepsilon_x + \frac{vE}{1-v^2} \varepsilon_y \quad (42)$$

The maximum horizontal stress σ_H can be obtained from the following equation:

$$\sigma_H = \frac{v}{1-v} \sigma_v + \frac{1-2v}{1-v} \alpha p_p + \frac{E}{1-v^2} \varepsilon_y + \frac{vE}{1-v^2} \varepsilon_x \quad (43)$$

Where σ_v is the vertical stress, v is the Poisson's ratio, p_p is the pore pressure, α is the Biot's coefficient, E is the static Young's modulus, and ε_x and ε_y are the tectonic strains in maximum and minimum horizontal stress direction, respectively. These two parameters were obtained by using the following equations:

$$\varepsilon_x = \frac{\sigma_v v}{E_s} \left(\frac{1}{1-v} - 1 \right) \quad (44)$$

$$\varepsilon_y = \frac{\sigma_v v}{E_s} \left(1 - \frac{v^2}{1-v} \right) \quad (45)$$

(6) Estimation of Rock Strength and Internal Friction Angle

The uniaxial compressive strength (UCS) can be calculated from the velocity of compressional wave using the following equation:

$$UCS = 10(V_p - 1) \quad (46)$$

Where the uniaxial compressive strength (UCS) is in MPa, V_p is the velocity of compressional wave in km/s.

Subsequently, the internal friction angle (φ) can be estimated using the empirical equation presented by [36] for high porosity formations:

$$\sin \varphi = \frac{V_p - 1}{V_p + 1} \quad (47)$$

Where φ is the internal friction angle in degrees and ϕ is porosity.

(7) Pore Pressure Prediction using Modified Eaton's Sonic Compressional Transit Time Method

Eaton (1975) proposed that sonic compressional transit time can be used to calculate pore pressure and its gradient. He presented the following equation to predict pore pressure gradient in shales using sonic compressional transit time:

$$p_p = \sigma_v - (\sigma_v - p_n) \left(\frac{\Delta t_n}{\Delta t} \right)^n \quad (48)$$

Where n is an exponent, and normally $n = 3$, Δt_n is the sonic compressional transit time or slowness in shales at normal pressure conditions, Δt is the sonic compressional transit time in shales obtained from sonic log.

Since it is difficult to determine the normal transit time in the condition of hydrostatic pore pressure in Eaton's original equation, the normal transit time (Δt_n) can be approached using a depth-dependent normal compaction trendline (NCT), whereas the equation proposed by [67] follows:

$$\Delta t_n = \Delta t_m + (\Delta t_{ml} - \Delta t_m)e^{-cZ} \quad (49)$$

Where Δt_m is the compressional transit time in the shale matrix, Δt_{ml} is the compressional transit time of the mudline, Z is the depth below the mudline, c is the compaction constant.

(8) Calculation of Minimum Mud Weight using Mohr Coulomb Failure Criterion

To calculate the minimum mud weight (p_m) using the elastic solutions with Mohr Coulomb failure criterion, the maximum principal stress needs to be determined beforehand.

The minimum and maximum tangential stresses at the wellbore wall in a vertical well can be obtained in the following form

$$\begin{cases} \sigma_{\theta \min} = 3\sigma_h - \sigma_H - p_m + \sigma_T, \theta = 0^\circ \\ \sigma_{\theta \min} = 3\sigma_H - \sigma_h - p_m + \sigma_T, \theta = 90^\circ \end{cases} \quad (50)$$

The minimum and maximum axial stresses at the wellbore wall can be obtained as follows:

$$\begin{cases} \sigma_{z \min} = \sigma_v - 2\nu(\sigma_H - \sigma_h) + \nu\sigma_T, \theta = 0^\circ \\ \sigma_{z \max} = \sigma_v + 2\nu(\sigma_H - \sigma_h) + \nu\sigma_T, \theta = 90^\circ \end{cases} \quad (51)$$

If the maximum tangential stress ($\sigma_{\theta \max}$) is the maximum principal stress, the required minimum mud weight (p_m) can be obtained:

$$p_m = \frac{3\sigma_H - \sigma_h - UCS + \alpha(q - 1)p_p + \sigma_T}{q + 1} \quad (52)$$

Where $q = \frac{1 + \sin \varphi}{1 - \sin \varphi}$.

(9) Calculation of Maximum Mud Weight using Tensile Failure Criterion

For a vertical well, the maximum mud weight can be calculated by using the following elastic solution:

$$\sigma_\theta = 3\sigma_h - \sigma_H - p_m + \sigma_T - \alpha p_p = T_0 \quad (53)$$

Therefore, the maximum mud weight (p_{max}) to generate tensile failures at the vertical wellbore wall can be obtained from the following equation by considering the Biot's coefficient $\alpha = 1$ when the tensile failure occurs:

$$p_{max} = 3\sigma_h - \sigma_H + \sigma_T - p_p + T_0 \quad (54)$$

Therefore, drilling-induced tensile failures will occur when the applied mud weight is greater than p_{max} in a vertical well.

3.5. Ethical Considerations

As this study utilizes proprietary well data from an active oil and gas operator, strict adherence to corporate confidentiality and formal non-disclosure agreements was maintained throughout the research process. All raw data matrices, specific geographic coordinates of the field, and sensitive operational parameters not strictly critical to the academic methodology have been anonymized or generalized. The analysis was conducted with absolute objectivity, ensuring that the geomechanical predictions are reported with academic integrity, devoid of data manipulation, to provide an unbiased assessment of the wellbore's structural limits.

4. RESULTS AND DISCUSSION

4.1. Field Overview

The South Sumatra Basin is a back-arc basin forming part of the Sunda Island Arc System, covering approximately 117,000 km² primarily onshore Sumatra, Indonesia [8]; [32]. The basin exhibits a dominant northwest-southeast structural trend, controlling the orientation of its grabens, faults, and anticlines [8]. Tectonically, the basin evolved through three major phases: extension during late Paleocene to early Miocene forming north-trending grabens; relative quiescence from early Miocene to early Pliocene; and Plio-Pleistocene compression and basin inversion, which reactivated faults and formed the anticlinal traps [8]; [57]. The stratigraphic succession consists of a dominantly clastic wedge deposited in a transgressive-regressive cycle, with key formations including the syn-rift Lahat Group, the deltaic Talang Akar Formation, the marine Gumai Formation shales, the Baturaja Formation limestones, and the regressive Air Benakat and Muaraenim Formations [27]; [32]. The lithology is predominantly sandstones, claystones, and shales, with important carbonate and coal intervals (Harsa, 1975). The petroleum system is sourced from Eocene-Oligocene syn-rift lacustrine and coaly facies containing Type II/III kerogen capable of generating both oil and gas, with reservoirs in Talang Akar sandstones, Baturaja carbonates, and fractured basement, sealed by intraformational and regional Gumai shales [32]. Hydrocarbons accumulate in anticlinal traps, with oil kitchens concentrated within graben systems, and crude oils are of terrestrial to lacustrine origin [32]; [53].

Well A is an exploratory well drilled vertically, located within the South Sumatra Basin, to a total depth of 2914 feet TVD. A comprehensive petrophysical well logging data was acquired over the drilled interval, which form the basis for constructing the 1D Mechanical Earth Model in this study. The available dataset includes caliper (CALI), gamma ray (GR), multiple resistivity logs (RXOZ, RLA1 through RLA5, RT), compressional sonic (DTCO) and shear sonic (DTSM) logs, density (RHOZ), thermal neutron porosity (TNPH), and photoelectric factor (PEFZ) logs. The sonic, density, and neutron porosity logs were utilized for geomechanical analysis, including the determination of rock mechanical properties, in-situ stresses, and pore pressure prediction. However, core sample and MDT (Modular Dynamic Testing) data were not available for geomechanical analysis in this study.

4.2. Data Assumptions

To execute the 1D-MEM analytically, several standard geomechanical assumptions are formally instituted. Primarily, the wellbore trajectory is assumed to be perfectly vertical, which geometrically simplifies the mathematical resolution of near-wellbore stress concentrations. The subsurface formations are modelled as linear elastic, isotropic, and poroelastic continuous media prior to macroscopic failure. It is assumed that the Biot's effective stress coefficient approaches unity for the highly porous intervals under investigation. Furthermore, in the absence of advanced core triaxial test data, the empirical relationships utilized to convert dynamic rock properties (derived from high-frequency well logs) to static rock properties are assumed to be regionally calibrated and valid for the specific lithology of Field Z.

4.3. Results and Discussion

(1) Overview

The 1 Dimensional Mechanical Earth Model constructed for Well A provides a continuous depth-dependent representation of the elastic properties, rock strength, pore pressure, and in-situ stress state required for wellbore stability assessment. The model covers the interval from approximately 1,289 to 2,689 m depth, within which the calculated geomechanical parameters exhibit substantial vertical variability.

The resulting MEM consists of three principal components. The first component comprises the formation mechanical properties, represented by Poisson's ratio, Young's modulus, cohesion, internal friction angle, and uniaxial compressive strength (UCS). The second component represents the in-situ stress state through the vertical stress, minimum horizontal stress, maximum horizontal stress, and pore pressure. The third component elaborates these properties and stresses into wellbore stability constraints, expressed through the lower and upper mud-weight boundaries.

Wellbore stability is governed by the interaction between the pre-existing stress field, pore pressure, mechanical strength, and the stress redistribution generated by drilling. Once the borehole is created, the original stress field is locally concentrated around the borehole wall, potentially producing shear failure and breakout under insufficient support or tensile failure when the wellbore pressure becomes excessive. Consequently, the mud-weight window is fundamentally a product of the combined mechanical and stress model.

(2) Construction and Evaluation of the Continuous Mechanical Earth Model

The construction of a continuous 1 Dimensional Mechanical Earth Model for Well A is conducted by integrating well log derived information into depth-dependent mechanical properties. The resulting profiles of Poisson's ratio, cohesion, internal friction angle, UCS, and Young's modulus are presented in Figure 5.1.

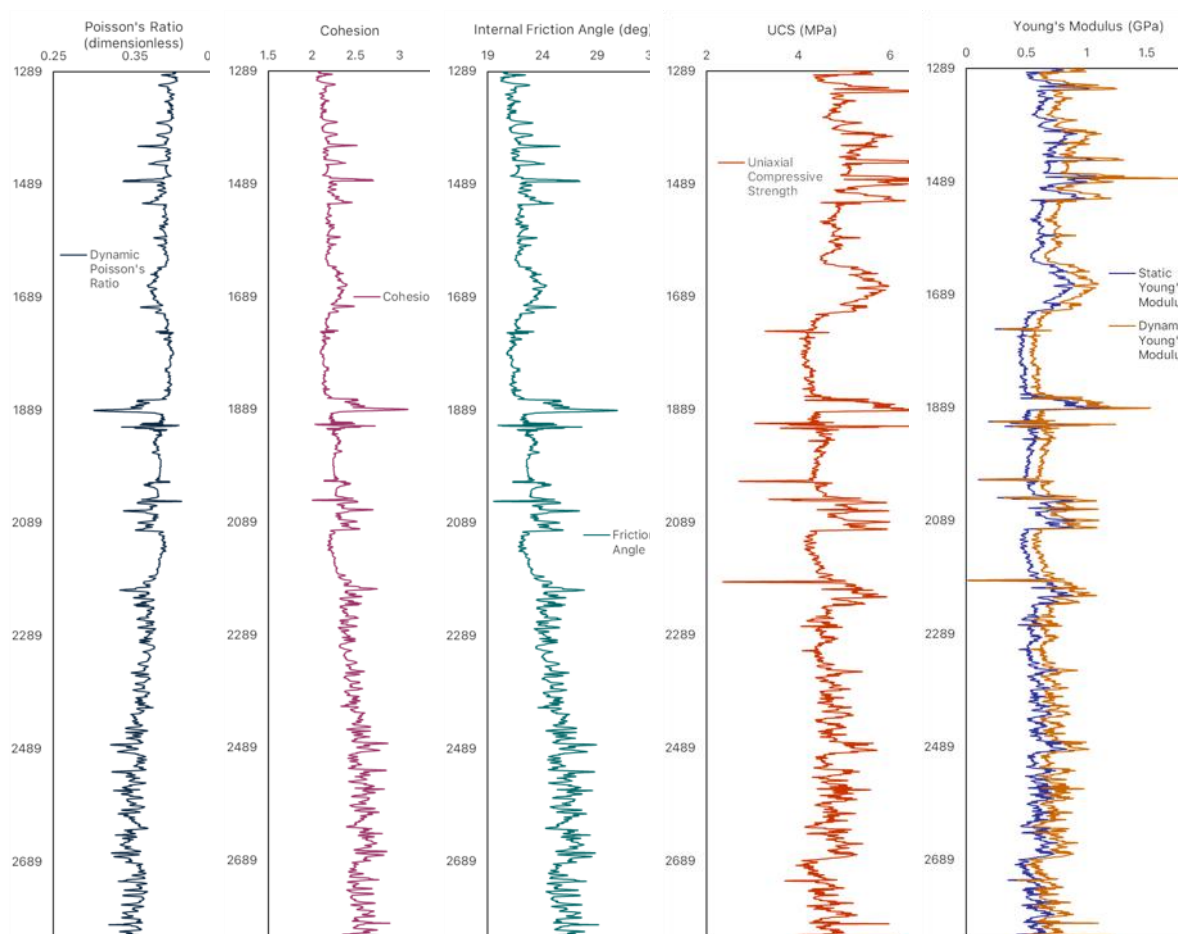


Figure 3. Continuous mechanical properties profile of Well A.

The calculated dynamic Poisson's ratio generally occupies a range of approximately 0.30–0.40, with most of the profile concentrated toward the middle-to-upper portion of this range. Several intervals exhibit lower values, whereas other intervals approach approximately 0.40. Poisson's ratio represents the relationship between lateral and axial deformation under elastic loading and consequently influences the conversion of vertical effective stress into horizontal stress within the poroelastic formulation. Therefore, the observed depth variation in Poisson's ratio contributes directly to the variation of the calculated horizontal stresses discussed subsequently.

The calculated cohesion predominantly occurs around approximately 2–3 MPa, with localized increases approaching the upper end of the plotted scale. The profile exhibits relatively stable behaviour over several sections but also contains distinct intervals of elevated cohesion and intervals where cohesion decreases. Since cohesion constitutes one of the principal shear-strength parameters in the Mohr–Coulomb formulation, these variations directly influence the predicted collapse resistance of the borehole.

The internal friction angle varies approximately from the low-20° range to more than 30°, with most of the interval displaying values around the mid-20° range. Several distinct excursions toward higher friction angles are visible, particularly around approximately 1,450–1,500 m and near 1,880–1,900 m. Because frictional resistance increases with increasing normal effective stress, the internal friction angle has a significant effect on the calculated shear-failure limit. Intervals possessing simultaneously low cohesion and low friction angle represent mechanically less resistant material and therefore deserve particular attention during mud-weight design.

The UCS profile exhibits a generally low-to-moderate strength range, approximately 3–6 MPa, with several localized excursions toward higher values. The substantial short-scale variation in UCS is important because the predicted collapse pressure is sensitive to the available rock strength at the borehole wall. The occurrence of relatively weak intervals throughout the modelled section means that a mud-weight program based solely on an averaged UCS would have the potential to underestimate localized instability.

The calculated Young's modulus shows a particularly pronounced difference between the dynamic and static estimates. The dynamic Young's modulus generally extends to approximately 1.5 GPa, whereas the static Young's modulus occupies a lower range, broadly around 0.3–0.9 GPa. The dynamic modulus displays substantially greater magnitude and variability relative to the static modulus.

The combined profiles indicate that the modelled section consists predominantly of relatively weak sedimentary material with substantial mechanical heterogeneity. The relatively low UCS values and modest cohesion indicate that the formation can be susceptible to shear failure when the effective stress concentration around the borehole becomes sufficiently large.

The mechanical weakness is especially important when considered together with the stress profile. Rock strength alone does not determine wellbore stability. A weak rock under a relatively benign stress state can remain stable, whereas a stronger rock exposed to a severe stress concentration can fail. Therefore, the intervals identified in Figure 5.1 as mechanically weak should subsequently be compared against the corresponding stress and mud-weight profiles.

(3) In-Situ Stress Profile Determination

The calculated in-situ stress profile is presented in Figure 5.2. The figure contains the vertical stress (σ_v), minimum horizontal stress (σ_h), maximum horizontal stress (σ_H), and pore pressure (p_p) over the modelled principal.

The ordering of the principal stresses is apparent throughout the modelled section.

$$\sigma_v > \sigma_H > \sigma_h \quad (55)$$

This ordering corresponds to a normal-faulting stress regime, because the vertical stress represents the greatest principal stress.

The stress profile shows that the vertical stress curve remains substantially higher than the horizontal stress curves across the modeled interval. The maximum horizontal stress remains above the minimum horizontal stress, producing a persistent horizontal stress anisotropy.

This stress anisotropy contributes to the development of localized circumferential stress concentrations around the wellbore. For a vertical well, the borehole wall experiences a redistribution of the far-field stresses, and the resulting tangential stress varies around the circumference. The locations experiencing the greatest compressive concentration therefore become preferential sites for shear failure and breakout.

(4) Wellbore Failure Analysis

The calculated stress and rock-strength profiles indicate that wellbore stability is strongly dependent on the local mechanical properties and stress conditions. Intervals characterized by relatively low UCS, cohesion, and Young's modulus are mechanically weaker and therefore require greater wellbore support to avoid shear failure.

The predicted mud-weight limits show that the minimum mud weight is primarily controlled by pore pressure and the requirement to prevent shear-induced wellbore collapse, whereas the maximum allowable mud weight is controlled by the onset of tensile failure or formation fracturing. The resulting separation between these limits defines the operationally acceptable mud-weight window.

The mud-weight profile shows substantial variation with depth. In several intervals, particularly around approximately 1,400–1,900 m and 2,000–2,300 m, pronounced changes in the calculated limits occur. These variations correspond with changes in the stress state and rock mechanical properties observed in the 1D-MEM.

The analysis therefore confirms that maintaining mud weight below the upper limit is necessary to avoid tensile failure and lost circulation, while maintaining it above the lower stability limit is necessary to prevent borehole collapse and breakout development.

(5) Field Validation Using Caliper Log

The caliper log was acquired for Well A and incorporated into the data-preparation quality-control workflow to identify borehole enlargement relative to the bit size. Localized caliper enlargement relative to the bit size occurs within the broader intervals around 1,400–1,900 m and 2,000–2,300 m, coinciding with portions where the predicted lower mud-weight boundary shows pronounced variation. This qualitative agreement supports the identification of mechanically sensitive intervals by the 1D-MEM.

Because the operator data are proprietary and the manuscript dataset does not retain a tabulated record of observed washout depths, breakout widths, or corresponding drilling events, a numerical depth-by-depth validation metric cannot be reported without introducing unsupported values. The caliper comparison is therefore treated as a qualitative field check, and the model should be interpreted accordingly rather than as a fully quantitatively validated field model.

(6) Predicted Mud Weight Window

The final mud-weight profile provides the operational window for Well A by combining pore pressure, shear-failure constraints, and tensile-failure limits. The calculated minimum mud weight follows the formation pressure and collapse-pressure requirements, while the maximum mud weight represents the upper pressure boundary before tensile failure and formation losses become likely.

The width of the safe mud-weight window varies significantly with depth. Wider windows occur where the formation has relatively high strength and sufficient separation between the lower and upper pressure limits. Conversely, narrow windows occur in mechanically weak or pressure-sensitive intervals, where relatively small changes in mud weight can shift the well from a stable condition toward collapse or fracturing.

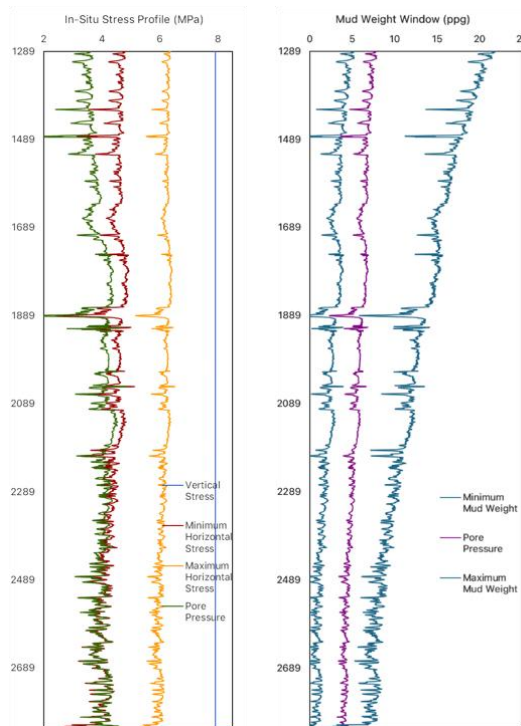


Figure 4. In-situ stress profile of Well A. & Predicted mud-weight window for Well A.

The results indicate that mud-weight optimization should therefore be depth-specific rather than based on a single value for the entire well. Operationally, the selected mud weight should remain above the predicted collapse/pore-pressure requirement while maintaining sufficient margin below the fracture limit. This is particularly important across the intervals exhibiting strong fluctuations in the calculated mud-weight boundaries.

The resulting mud-weight window provides a practical basis for drilling-fluid design and wellbore-pressure management in Well A. Similar applications of geomechanical modelling have demonstrated that incorporating formation strength, stress state, and pore pressure into mud-window prediction can reduce the likelihood of wellbore instability and associated non-productive time [2]; [1]; [63].

(7) Sensitivity Analysis of Dynamic-to-Static Young's Modulus Conversion

To evaluate the uncertainty introduced by converting dynamic Young's modulus to static Young's modulus in the absence of core calibration, a parametric sensitivity analysis was conducted around the baseline correlation $E_s = 0.8186 \times E_d$. Five cases were considered: -20%, -10%, baseline, +10%, and +20% relative to the baseline static Young's modulus.

The sensitivity result is governed by the formulation of the poroelastic horizontal stresses. The tectonic strain terms ε_x and ε_y are each inversely proportional to E_s , while the horizontal-stress equations multiply those strain terms by E_s . Consequently, the E_s dependence cancels when the strain equations are substituted into the horizontal-stress equations. The calculated σ_H and σ_h therefore remain unchanged across the tested conversion factors, and the resulting collapse and tensile mud-weight boundaries are likewise unchanged.

Accordingly, the analytical sensitivity of the predicted mud-weight window to the dynamic-to-static Young's modulus conversion is 0% within the present formulation. This result is conditional on the adopted tectonic-strain equations; uncertainty in static Young's modulus may affect the model if independently measured or otherwise fixed tectonic strains are used instead.

Table 1

Sensitivity case	Static Young's modulus	σ_H and σ_h	Mud-weight boundaries
-20%	0.80E _{s,0}	Unchanged (0%)	Unchanged (0%)
-10%	0.90E _{s,0}	Unchanged (0%)	Unchanged (0%)

Baseline	1.00E s,0	Unchanged (0%)	Baseline
+10%	1.10E s,0	Unchanged (0%)	Unchanged (0%)
+20%	1.20E s,0	Unchanged (0%)	Unchanged (0%)

5. CONCLUSIONS

The 1-Dimensional Mechanical Earth Model for Well A integrates sonic and density well logs with pore pressure data to characterize the formation's mechanical properties and in-situ stress state. The model indicates a normal-faulting stress regime with persistent horizontal stress anisotropy and mechanically weak intervals characterized by relatively low UCS and cohesion. Application of the Mohr–Coulomb and tensile failure criteria define a depth-dependent mud-weight window in which the lower boundary is governed by pore pressure and collapse resistance, while the upper boundary is controlled by tensile failure. The resulting window provides a site-specific basis for drilling and well-intervention planning.

Recommendations

- Future operations should prioritize the acquisition of physical core samples to conduct continuous triaxial compressive tests. This will allow for the local calibration of the dynamic-to-static property correlations, significantly reducing uncertainty in the UCS and Poisson's ratio estimations.
- While the current model establishes a baseline minimum mud weight, future iterations should evaluate the utilization of true-triaxial failure criteria, such as Mogi-Coulomb or Modified Lade, which account for the strengthening effect of the intermediate principal stress and may safely widen the operational mud weight window.
- During active drilling or intervention, the predicted minimum mud weight model should be coupled with real-time monitoring of cavings geometry at the shale shakers. Splintery cavings will serve as a physical validation of shear failure, allowing for real-time calibration of the 1D-MEM.
- To account for structural complexities, fault presence, and depletion effects over time, the insights from this 1D model should be integrated into a field-wide 3D geomechanical model to optimize future horizontal drilling and multi-stage stimulation campaigns.

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NOMENCLATURE

Symbol	Definition	Unit
σ_n	Normal stress	MPa
τ	Shear stress	MPa
σ_v	Vertical/overburden stress	MPa
σ_H	Maximum horizontal stress	MPa
σ_h	Minimum horizontal stress	MPa
σ_1	Maximum principal stress	MPa
σ_2	Intermediate principal stress	MPa
σ_3	Minimum principal stress	MPa
σ'	Effective stress	MPa
p_p	Pore pressure	MPa
p_m	Mud-weight pressure equivalent	MPa
α	Biot's effective stress coefficient	dimensionless
E_d	Dynamic Young's modulus	GPa
E_s	Static Young's modulus	GPa
E	Young's modulus used in poroelastic stress equations	GPa
K_d	Dynamic bulk modulus	GPa
K_m	Matrix bulk modulus	GPa
μ_d	Dynamic shear modulus	GPa
V_p	Compressional-wave velocity	km/s
V_s	Shear-wave velocity	km/s
Δt_p	Compressional transit time	$\mu\text{s}/\text{ft}$
Δt_n	Normal-compaction-trend transit time	$\mu\text{s}/\text{ft}$
Δt_m	Mudline transit time	$\mu\text{s}/\text{ft}$
Δt_{ml}	Transit-time reference term	$\mu\text{s}/\text{ft}$
ρ_b	Bulk density	g/cm^3
ρ_0	Reference density	g/cm^3
g	Gravitational acceleration	m/s^2

z	Depth below mudline	m
z_0	Reference depth	m
ν_d	Dynamic Poisson's ratio	dimensionless
ν_s	Poisson's ratio	dimensionless
φ	Internal friction angle	degrees
c	Cohesion	MPa
UCS	Uniaxial compressive strength	MPa
q	Mohr–Coulomb stress ratio	dimensionless
μ	Coefficient of friction	dimensionless
ε_x	Tectonic strain in maximum horizontal stress direction	dimensionless
ε_y	Tectonic strain in minimum horizontal stress direction	dimensionless
θ	Circumferential angular position around the wellbore	degrees
σ_T	Tensile stress term	MPa
T_0	Tensile-strength threshold	MPa
φ_D	Corrected density porosity	fraction
φ_N	Corrected neutron porosity	fraction
φ_{corr}	Corrected effective porosity	fraction
K_{dry}	Dry-rock/frame bulk modulus	GPa
n	Eaton exponent	dimensionless
c_z	Compaction constant in the normal compaction trend	1/m