

A CONTRIBUTION TO THE STUDY OF THE STABILITY OF PRODUCING OIL WELLS – THE CASE OF THE LIBWA-12 DOUBLE LATERAL WELL IN THE UPPER-PINDA 3 RESERVOIR

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DOI: 10.51865/JPGT.2026.02.11

ABSTRACT

The oil industry faces the constant challenge of optimising hydrocarbon recovery whilst ensuring the mechanical integrity of wells. This study assesses the geomechanical stability of the Upper-Pinda 3 reservoir in the Libwa field (DRC), focusing on the impact of the architectural complexity of the Libwa-12 well (double lateral) and reservoir depletion.

Using a numerical workflow implemented in Python (Google Colab/Jupyter Notebook) and based on Kirsch's equations coupled with Biot's poroelasticity theory, a model of in situ stress redistribution around the laterals was developed. The implementation was checked for unit consistency and benchmarked against the closed-form Kirsch solution for the vertical-well reference case. The results demonstrate that a reduction in reservoir pressure from 2667 to 1567 psia causes the Mohr circle to migrate towards the Mohr–Coulomb failure envelope, despite a moderate Biot coefficient of 0.54.

A comparative analysis of the two sidetracks reveals that the 12.19° inclination of sidetrack 2 induces an asymmetric redistribution of tangential stresses, thereby reducing the operational stability window compared with the vertical reference case. Finally, the estimated sand production of around 12.45 kg/m confirms that the reservoir has entered a state of generalised failure, where mechanical collapse of the borehole wall becomes the main driver of instability. This work highlights the need for coupled modelling to ensure the sustainability of extraction in complex and depleted formations.

Keywords: geomechanics, well stability, poroelasticity, Mohr-Coulomb criterion, dual lateral, depletion, Libwa field.

INTRODUCTION

The oil industry currently faces a major and ongoing challenge in optimizing hydrocarbon recovery whilst ensuring operational safety. In this quest for performance, well stability has become a critical and strategic factor. Indeed, an unstable well leads to costly incidents, such as wall collapse, sand production or stuck packers, threatening the structural integrity of the well and even its economic viability. As Jaeger and Cook [1] demonstrated in their seminal work on rock mechanics, the failure of a rock formation is not a random event, but the result of an imbalance between in situ stresses and the intrinsic strength of the rock, often modelled using the Mohr-Coulomb and/or Drucker-Prager failure criteria [2]. A model for calculating

hydration stresses around the wellbore based on experimental results from shale formations was developed by Yew et al [3]. The mechanical model of wellbore stability for a formation with a plane of weakness under pore flow thus considers the effect of pore flow on the plane-of-weakness model developed by Lu et al [4]. Jin et al [5] established a mechanical model of wellbore stability under large displacement by systematically analysing the stress distribution around the wellbore. Ding et al [6] considered the effects of anisotropic permeability in the laminar planes of stratified shales and proposed a new stability model. Zou et al [7] developed a mechanical model of stable in-plane deformation for gas wells, considering the degradation characteristics around the wellbore under uniformly and non-uniformly distributed loads. Tang et al [8] studied well stability during completion and production tests by analysing the mineral composition of the reservoir rock, the microscopic pore structure and the mechanical properties of the rock. Wei et al [9] proposed a geomechanical and fluid flow model, considering the anisotropic intrusion of drilling fluid into natural fractures. Li et al [10] employed experimental and numerical simulation methods and considering temperature variations in the surrounding environment. Gao et al [11] developed a poro-thermo-elastic model that accounts for the effects of dynamic thermal disturbances at the boundaries on the stability of fractured porous rocks. Wang et al [12] developed a finite-element hydraulic coupling model for well instability by incorporating a disturbance degradation factor into the classical Mohr-Coulomb creep criteria. Gomar et al. [13] used a thermo-poroelastic model fully coupled with the transport process via conduction and convection to analyze the stability and failure of wells. Furthermore, Gomar et al [14] took into account the effects of solid particles and employed a thermal-mechanical model of the well that was fully coupled with the transport processes of conduction and convection, carrying out a transient thermo-poroelastic finite element analysis that was fully coupled with the stability of the well. Braun [15] presented the three main factors influencing the effective soil stress associated with well stability and suggested appropriate methods to address them. Westegard [16] studied the stress distribution in a deep well and applied this to well geotechnics. Yu et al [17] proposed a model combining chemical and mechanical effects after taking water flow into account. Liang et al [18] developed a coupled flow and mechanisation model for well stability, taking into account hard and brittle shale formations. Junyan et al [19] carried out a finite element simulation to study well stability under various operational and geomechanical conditions.

The Upper-Pinda 3 reservoir in the Libwa field, the focus of our study, exhibits complex geomechanical and petrophysical characteristics. During the production phase, two key factors must be considered to ensure the long-term viability of extraction. These are variations in pore pressure and in-situ stresses. According to research by B.S. Aadnoy [20], the orientation of a well relative to horizontal stresses determines its stability window. These disturbances can therefore weaken the formation, particularly in advanced well configurations. Our study focuses on two distinct well architectures in this field: the Libwa-12 well (double lateral). The latter features a complex design which, whilst increasing the contact area with the reservoir, creates multiple potential weak points at the branching points and along the horizontal drains. We therefore asked ourselves the following questions:

- To what extent does the double-lateral configuration of the Libwa-12 well increase the risk of instability?
- What is the impact of depletion of the Upper-Pinda 3 reservoir on changes in in situ stress, and what are the predominant failure modes observed in this formation?

MATERIALS AND METHODS

The study was carried out using Python in Anaconda/Jupyter Notebook. The input dataset was compiled from the geological drilling report for the Libwa-12 double-lateral well, from which density and P-wave/S-wave transit times were extracted to estimate the geomechanical properties of the Upper-Pinda 3 reservoir and to build the numerical input tables. The parameters were first assembled in CSV format and then imported into the Python workflow. Gemini was used only as a programming assistant during code drafting and debugging; it was not used to interpret results or to make scientific decisions.

The numerical workflow was validated in three ways: (i) unit harmonisation and dimensional-consistency checks were carried out before each simulation; (ii) the stress field for the vertical-well reference case was compared with the analytical closed-form Kirsch solution at representative azimuths; and (iii) selected outputs were manually recalculated from the corrected input tables before figure generation. Only the human-checked outputs were retained for interpretation.

Research into well geomechanics is based on the following premise: ‘while material properties define the framework and environmental constraints dictate the load, it is analytical modelling that ensures convergence towards a stable equilibrium of the well-formation system. [21]

Characterisation of in-situ stresses

The authors postulate that the stability of a well is intrinsically linked to the disturbance of the undisturbed stress field caused by the introduction of a cylindrical cavity. The analysis is based on the precise determination of the stress tensor ($\sigma_v, \sigma_H, \sigma_h$). [22]

The redistribution of circumferential stresses is modelled using Kirsch’s equations [23]. These equations enable the calculation of how stresses and pressure concentrate and distribute around the well. The solution to Kirsch’s equations for a well of radius r subjected to the stress tensor yields either effective radial, tangential (circular) or shear stresses. For our study, this must be coupled with Biot’s theory. Thus, our analysis focuses on the system:

$$\left\{ \begin{array}{l} \sigma'_{rr}(r, \vartheta) = \frac{\sigma_H + \sigma_h}{2} \left(1 - \frac{a^2}{r^2}\right) + \frac{\sigma_H - \sigma_h}{2} \left(1 - 4\frac{a^2}{r^2} + 3\frac{a^4}{r^4}\right) \cos(2\theta) + P_w \frac{a^2}{r^2} + \eta(P_w - P_p) \left(1 - \frac{a^2}{r^2}\right) - \alpha P_p(r) \\ \sigma_{\theta\theta} = \frac{\sigma_H + \sigma_h}{2} \left(1 + \frac{a^2}{r^2}\right) - \frac{\sigma_H - \sigma_h}{2} \left(1 + 3\frac{a^4}{r^4}\right) \cos(2\theta) - P_w \frac{a^2}{r^2} - \eta(P_w - P_p) \left(1 - \frac{a^2}{r^2}\right) + 2\eta(P_w - P_p) \frac{a^2}{r^2} - \alpha P_p(r) \\ \sigma_{r\theta} = -\frac{\sigma_H - \sigma_h}{2} \left(1 + 2\frac{a^2}{r^2} - 3\frac{a^4}{r^4}\right) \sin(2\theta) \\ \sigma_{zz} = \sigma_v - 2\nu(\sigma_H - \sigma_h) \left(\frac{a^2}{r^2}\right) \cos(2\theta) + \eta(P_w - P_p) \left(\frac{a^2}{r^2}\right) - \alpha P_p(r) \end{array} \right. \quad (1)$$

where σ_{rr} is the effective radial stress, $\sigma_{\theta\theta}$ is the effective tangential (circular) stress, σ_{zz} is the effective axial stress, and $\sigma_{r\theta}$ is the shear stress in a plane perpendicular to the z -direction; the angle θ is the angle between the direction of σ_H and the point at which the stress is measured. The distance r is measured from the centre of the well. P_w is the well pressure (at the bottom of the well) and P_p is the reservoir pressure. η is poroelastic stress gradient given by $\alpha \frac{1-2\nu}{2(1-\nu)}$.

Breaking criteria

For most rocks, the change in rock strength with confining pressure can be described in terms of a linearised Mohr-Coulomb failure envelope. This envelope can be expressed in terms of shear stress and normal stress in Mohr’s space (σ, τ coordinates) as follows [24]:

$$\tau = S_0 + \sigma_n \mu_i \quad (2)$$

where:

- τ : shear stress;
- S_0 : cohesion;
- μ_i : internal friction coefficient of the rock, which is the tangent of its angle of internal friction ϕ ($\mu_i = \tan \phi$).

Mohr's circle is a graphical method for transforming the stress tensor; it provides a useful representation for predicting failure limits when plotted on the same graph as the Mohr–Coulomb failure envelope, as shown in Figure 1 [25]. The transformation equations are as follows:

$$\sigma_n = \frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2} \cos(2\theta) \quad (3)$$

$$\tau = \frac{\sigma_1 - \sigma_3}{2} \sin(2\theta) \quad (4)$$

In Equations (3) and (4), the trigonometric terms are written explicitly as $\cos(2\theta)$ and $\sin(2\theta)$ to avoid ambiguity in the numerical implementation.

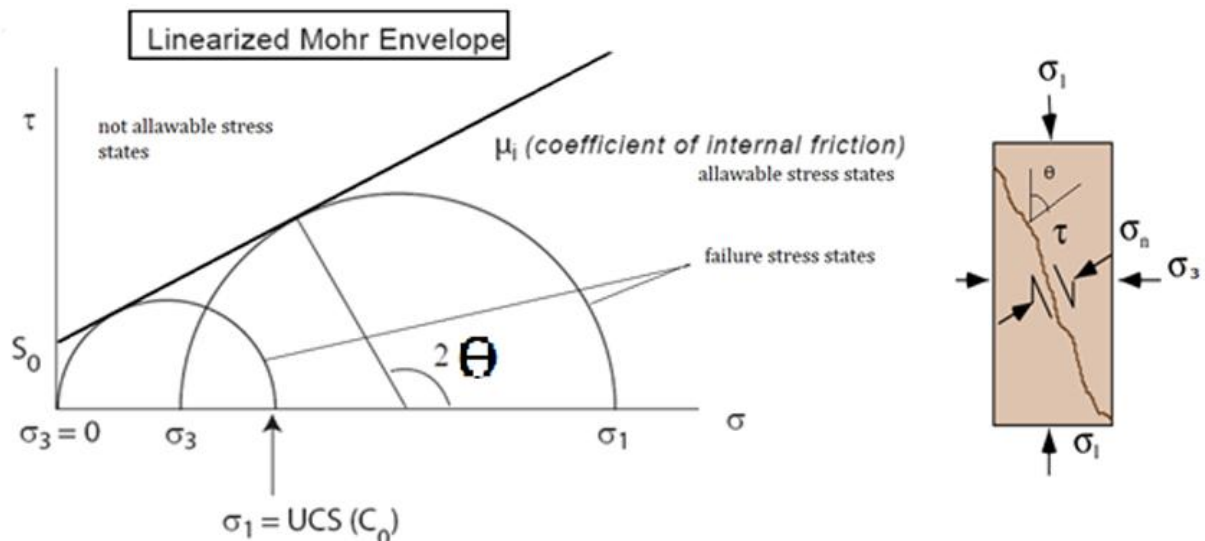


Figure 1. Mohr–Coulomb failure criterion.

Basic model assumptions

To carry out this advanced analysis of the Upper-Pinda 3 reservoir for the Libwa-12 double-lateral well, we need to couple two phenomena:

- Poro-elasticity: The reduction in pore pressure during depletion leads to a reduction in in-situ horizontal stresses in accordance with the poroelastic coupling coefficient.
- Poro-plasticity: We use a failure criterion (Mohr–Coulomb) to determine whether the rock reaches its plasticity (failure) threshold due to the increase in effective stresses caused by the pressure drop.

Model parameters

The Libwa field is one of the producing oil fields in the Democratic Republic of the Congo basin, discovered in 1981 and producing from the Upper Pinda formation. The present study focuses on the Lib-12 double-lateral well. Before numerical implementation, the geomechanical properties were harmonised in a consistent engineering unit system. Table 1 therefore reports the corrected working values used in the revised analysis. In Table 2 are presented geometric and field parameters of the Lib-12 double-lateral well. Table 3 represent a summary of calculated stresses. Figure 2 reveal production profile estimated based on the initial pressure of depleted 2018 pressure state.

Table 1. Geomechanical and petrophysical parameters of the Lib-12 double-lateral well.

Parameters	Initial condition	Start of production	Production in 2018
Young's modulus (GPa)	89,83	89,83	89,83
Tensile modulus (GPa)	35,76	35,76	35,76
Rock modulus of elasticity (GPa)	59,58	59,58	59,58
Poisson ratio (-)	0,25	0,25	0,25
Internal friction angle (°)	29,3	29,3	29,3
Cohesion (MPa)	9.10526	9.10526	9.10526
Uniaxial compressive strength, UCS (MPa)	30.96	30.96	30.96
Tensile strength (MPa)	3.10	3.10	3.10
Biot coefficient (-)	0,54	0,54	0,54
Reservoir pressure (psia)	2667	2667	1567
Porosity of the reservoir (-)	0,19	0,19	0,19
Permeability (mD)	0,58	0,58	0,48

Table 2. Geometric and field parameters of the Lib-12 double-lateral well.

Parameters	Value
Depth of side well 1	3553 m
Depth of side well 2	3548.3 m
Lateral inclination 2	12.19°
Well diameter (lateral 1 and 2)	215,9 mm
Reservoir pressure (psia)	2667
Density (g/cm ³)	2.31-2.62

Table 3. Summary of calculated stresses.

Parameters	Value in psi	Value in MPa	Gradient
Pore pressure Pp	2667	18,38	0,49 psi/ft
Vertical stress, σ_v	5366,30	37,00	0,99 psi/ft
Minimum horizontal stress	3566,80	24,53	0,66 psi/ft
Maximum horizontal stress	3971,80	27,38	0,74 psi/ft
Vertical effective stress	2699,30	18,61	-
Effective minimum horizontal stress	899,80	6,20	-
Effective maximum horizontal stress	1304,80	8,99	-

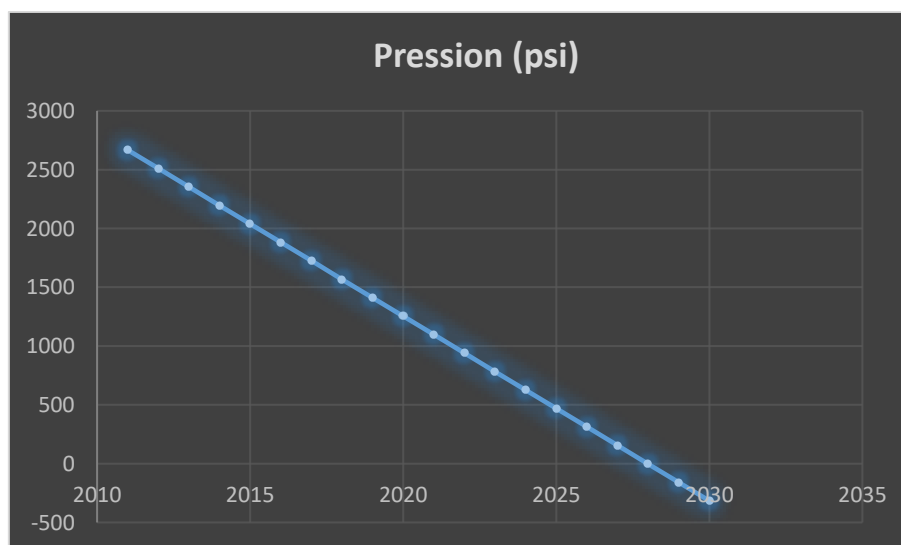


Figure 2. Production profile estimated based on the initial pressure of depleted 2018 pressure state.

RESULTS

Using the corrected input data (Tables 1–3) and Figure 2 together, the Python workflow was used to visualise depletion- and stress-related failure around laterals 1 and 2 of the Lib-12 well. The figures reproduced below were prepared from the Python outputs as publication figures, with English labels and without notebook-interface elements.

Regarding Figure 3, it can be observed that effective radial stress values near the wellbore are low, in contrast to those further away. Conversely, effective tangential stress values are high near the wellbore in north-south orientation.

Figure 4, in turn, shows low shear stress values in the directions of the intervals $[90^\circ, 180^\circ]$ and $[270^\circ, 360^\circ]$, whereas they are critical in the directions $[0^\circ, 90^\circ]$ and $[180^\circ, 270^\circ]$.

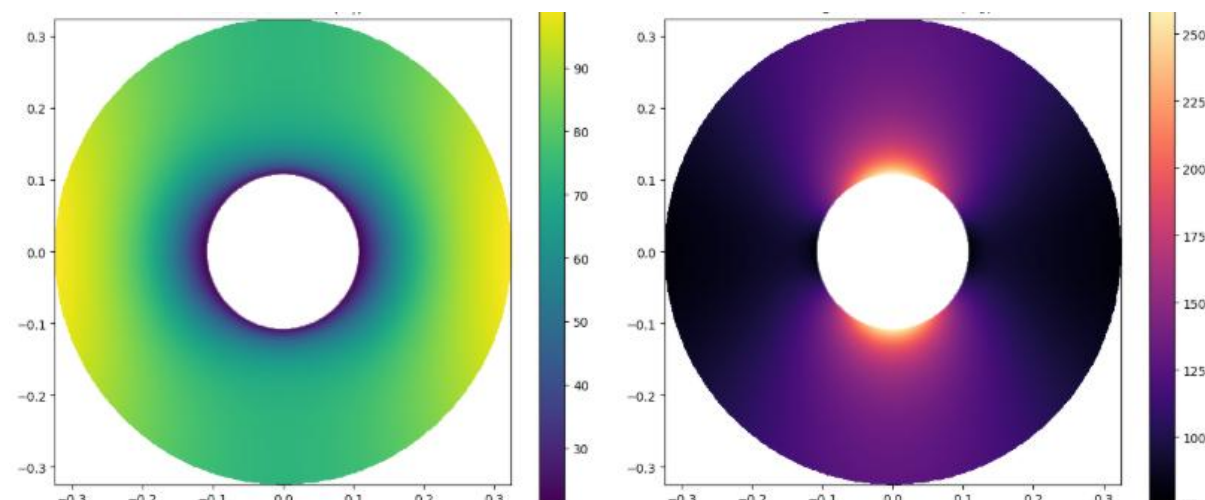


Figure 3. 2D visualization of the effective radial and tangential stresses around Lib-12 lateral 1.

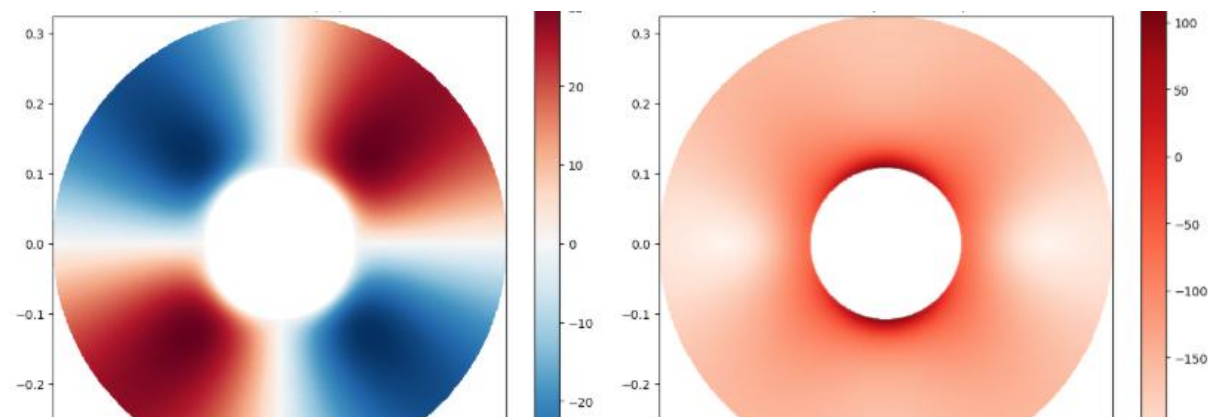


Figure 4. 2D Visualization of the effective shear stresses and plastic failure zone around Lib-12 lateral 1.

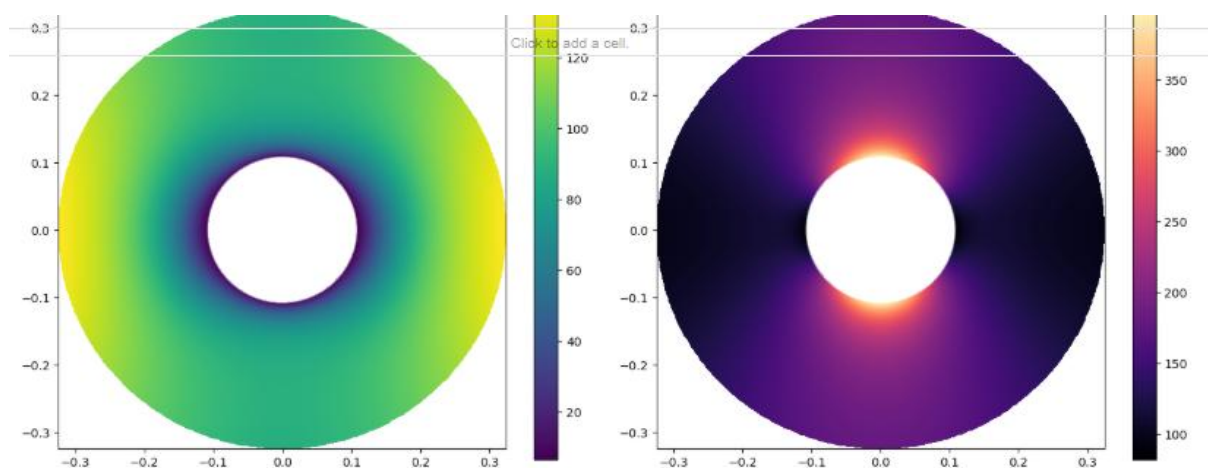


Figure 5. 2D visualization of the effective radial and tangential stresses around Lib-12 lateral 2 (inclination 12.19°).

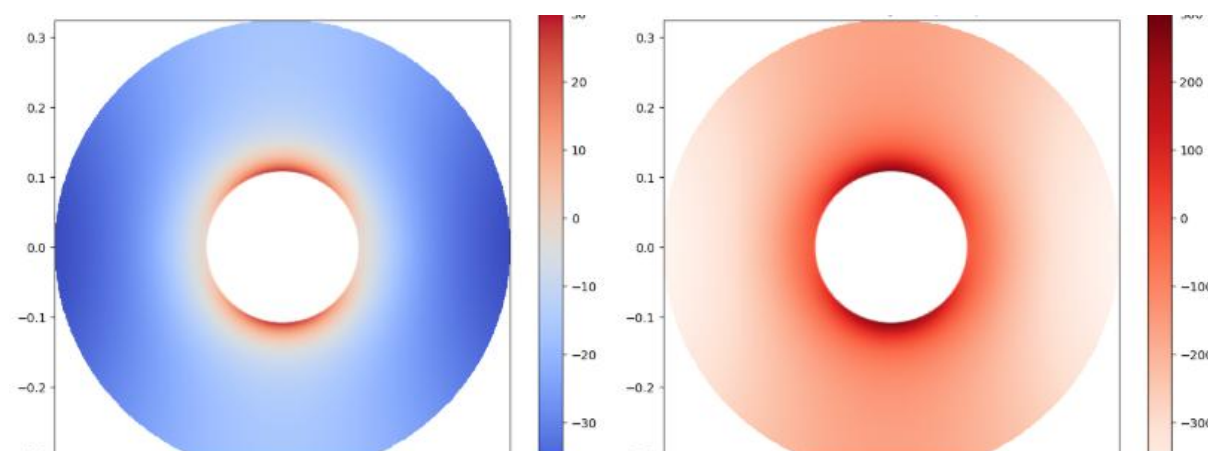


Figure 6. 2D visualization of the effective shear stresses and plastic failure zone around Lib-12 lateral 2.

Regarding Figure 5, we note that the effective radial stress values near the wellbore are low around the wellbore, though higher than the effective radial stresses in lateral 1. Unlike the values observed further away. Effective tangential stress values near the wellbore mirror those observed in lateral 1, except that the values associated with tangential risk exceed 330MPa.

In Figure 6 reveals high shear stress values around the wellbore, indicating a high risk of shear failure; however, unlike in figure 4, there is no specific failure orientation, a fact explained by the inclination and the junction of deviated drain in lateral 2.

CONCLUSIONS

Analysis of the Libwa-12 double-lateral well shows that the stability of the Upper-Pinda 3 reservoir is governed by a strong coupling between pore pressure and effective stresses. With a Biot coefficient of 0.54, the rock exhibits moderate but significant sensitivity to depletion. The pressure drop from 2667 to 1567 psia induces volumetric contraction of the matrix, but the reduction in total horizontal stresses does not compensate for the loss of fluid support. This results in a migration of the Mohr circle towards the Mohr-Coulomb failure envelope, thereby increasing the stress deviation and the risk of failure around the wellbore.

Added to this is the effect of the well architecture. Lib-12 lateral 2 has an inclination of 12.19° (generated by a 2°/100 ft build), which alters the circumferential distribution of tangential stress. In the vertical-well reference case, failure is symmetrical and centred on the azimuth of the minimum horizontal stress, whereas in the deviated well an asymmetrical redistribution is observed. The introduction of a vertical-stress component in the borehole cross-section amplifies stress concentrations at critical points and reduces the operational stability window compared with the vertical model.

The estimated sand mass (~12.45 kg/m) indicates that the reservoir is entering a state of widespread failure. Scientifically, this means that fluid-flow velocity is no longer the sole factor in sand generation; the mechanical collapse of the borehole wall is also feeding the sediment flow. The modelling results therefore support the need for combined depletion management and wellbore-stability control in the Upper-Pinda 3 reservoir.

NOMENCLATURE

σ'_{rr} : effective radial stress;	UCS: uniaxial compressive strength;
$\sigma'_{\theta\theta}$: effective tangential (hoop) stress;	S_{Hmax} : maximum horizontal stress;
σ'_{zz} : effective axial stress;	S_{Hmin} : minimum horizontal stress;
$\tau_{r\theta}$: shear stress in the borehole cross-section;	α : Biot coefficient;
P_w : wellbore pressure;	φ : internal friction angle.
P_p : reservoir pressure;	

AI TOOL USAGE STATEMENT

The authors used Gemini only for limited programming assistance, namely code drafting and debugging within the Python/Google Colab/Jupyter workflow. No AI tool was used to generate scientific conclusions or to replace author judgement. All outputs influencing the manuscript, tables and figures were reviewed, corrected and validated by the authors, who take full responsibility for the content of the paper.

DATA AND CODE AVAILABILITY

A minimal reproducibility package accompanying this revised submission includes the cleaned input tables and an example Python implementation of the analytical workflow used in this study. These files are supplied as Supplementary Material for peer review and should be deposited in a trusted repository with a persistent DOI or URL before final publication, if required by the journal.

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Received: July 2026; Revised: September 2026; Accepted: October 2026; Published: October 2026