



Investigating the effect of wellbore deviation on its stability in carbonate formations (Water-based drilling fluid)

Investigación del efecto de la desviación del pozo en su estabilidad en formaciones carbonatadas (fluido de perforación a base de agua)

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Article Data

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Abstract

Well instability is one of the main problems in the drilling aspect. This can be managed by determining a window for the drilling mud considering the mechanical properties of the formation. Pore pressure and orientation of the main stresses in situ are essential parameters for determining the safe sludge weight window. This article aimed to determine a safe mud weight window for vertical and deviated wells under underbalanced drilling conditions. A carbonate formation was chosen for numerical modeling of the well using FLAC software. Several oil wells in Iran were selected as representative carbonate formations for research purposes. A numerical model of the well was constructed using well log data and calibrated with laboratory results and drill reports. To verify the numerical results, the Mohr-Coulomb failure criterion was used. Therefore, an elastic porous model and finite difference codes were generated to determine the mud weight window for the designated wells. Also, choosing a numerical analysis method is crucial and should be considered. The numerical model used in this study can be used to simply and reliably determine the safe mud weight window and the required pit path.

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Resumen

La inestabilidad del pozo es uno de los principales problemas en el aspecto de la perforación. Esto se puede gestionar determinando una ventana para el lodo de perforación considerando las propiedades mecánicas de la formación. La presión de los poros y la orientación de las tensiones principales in situ son parámetros esenciales para determinar la ventana segura de peso del lodo. Este artículo tuvo como objetivo determinar una ventana segura de peso de lodo para pozos verticales y desviados bajo condiciones de perforación subbalanceadas. Se eligió una formación de carbonato para el modelado numérico del pozo utilizando software FLAC. Varios pozos petrolíferos de Irán fueron seleccionados como formaciones carbonatadas representativas para fines de investigación. Se construyó un modelo numérico del pozo utilizando datos de registro de pozos y calibrado con resultados de laboratorio e informes de perforación. Para verificar los resultados numéricos, se empleó el criterio de fallo de Mohr-Coulomb. Por ello, se generó un modelo poroso elástico y códigos de diferencias finitas para determinar la ventana de peso del lodo para los pozos designados. Además, la elección de un método de análisis numérico es crucial y debe considerarse. El modelo numérico empleado en este estudio puede emplearse para determinar de forma sencilla y fiable la ventana segura de peso de barro y el camino del pozo requerido.

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Introduction

Maintaining wellbore stability is one of the most critical challenges in drilling operations, as instability can lead to severe operational problems, including wellbore collapse, stuck pipe, excessive torque and drag, and in extreme cases, loss of the well^{1,2}. These issues significantly increase non-productive time and drilling costs, particularly in complex geological environments such as fractured carbonate formations^{3,4}. Wellbore instability arises from the interaction between *in-situ* stresses, formation mechanical properties, pore pressure, drilling fluid pressure, and wellbore geometry. Among these factors, drilling mud weight plays a decisive role in controlling both shear and tensile failures around the wellbore^{5,6}.

In recent years, underbalanced drilling (UBD) has been increasingly adopted in mature carbonate reservoirs due to reservoir pressure depletion and the need to enhance productivity^{7,8}. In UBD operations, the hydrostatic pressure of the drilling fluid is intentionally kept lower than the formation pore pressure, which can reduce formation damage, improve rate of penetration, and mitigate severe mud losses^{9,10}. However, lowering the mud weight also reduces the mechanical support provided to the wellbore wall; thereby increasing the risk of wellbore instability, especially in formations with complex stress regimes and natural fractures^{9,11}. Wellbore deviation further complicates the stability problem^{12,13}. While deviated and horizontal wells offer environment and economic advantages by increasing reservoir contact, deviation alters the stress distribution around the wellbore and generally reduces mechanical stability compared to vertical wells^{14,15}.

As the deviation angle increases, the likelihood of shear and tensile failures around the wellbore wall also increases, particularly under underbalanced drilling conditions^{16,17}.

Consequently, determining a reliable and safe mud-weight window for both vertical and deviated wells remain a critical and challenging task in well design. Accurate determination of the mud weight window requires knowledge of the geomechanical properties of the formation and stress state, as well as the application of analytical or numerical methods^{18,19}. Although analytical failure criteria are commonly used for preliminary evaluations, numerical modeling provides a more comprehensive framework for capturing the complex interaction between stresses, rock properties, wellbore geometry, and drilling fluid pressure^{20,21}.

The objective of this study was to investigate the effect of well deflection on well stability in carbonate formations under subbalanced drilling conditions, determining the safe mud weight window for both vertical and deflected wells. To achieve this goal, numerical models of wells were developed using FLAC software and calibrated with field, logs, and laboratory data from a carbonate reservoir. The results will be used to evaluate the variation of the mud weight window with the deflection angle and identify the most stable well trajectory under underbalanced drilling conditions.

Materials and methods

Determination of Drilling Mud Window in Vertical and Directional Wells Using FLAC Software. The upper and lower bounds of the drilling mud window can be used to predict and prevent the formation of tensile and shear fractures around a wellbore. In this section, in this section, FLAC software was used as a numerical method to examine the factors involved in determining the drilling mud window. Numerical methods have a wide range of applications in solving

engineering problems. It is important to note that accurately solving geomechanical problems using only empirical or numerical methods is not feasible. The combination of these two approaches can assist in addressing complex geological issues. The foundation of numerical methods lies in the conversion of a continuum with infinite degrees of freedom into a system with a finite number of degrees of freedom at specific points within the domain. The position, number, and relationships between these points are defined through mesh generation.

By utilizing the available software and precisely defining the geometry, boundary conditions, strength, and deformability properties of the rock mass, an acceptable design can be achieved. Numerical methods allow for the modeling of surface and underground structures with any shape and cross-section, providing insights into stresses and displacements at all desired points. These methods also enable the analysis of drilling processes, maintenance, and impact of water flow on the stability of rock and soil masses, including wellbore walls.

The finite difference method (FDM) is one of the oldest numerical techniques for solving systems of differential equations and continues to be widely used in engineering problem-solving. Similar to the finite element method (FEM), FDM continuously models the problem space with elements that are connected at nodes. However, the advantage of the FDM is that it requires less computational power for processing. Numerous researchers, including Wilkins in 1963, have demonstrated that the results obtained from FDM and FEM are identical for certain problems. However, the FDM is generally more flexible than the FEM.

The FLAC is one of the most important software tools that utilizes the finite-difference method for

solving geomechanical problems. The FLAC (fast lagrangian analysis of continua) is a numerical computational tool based on explicit finite differences that simulate the structural behavior of formations composed of soil, rock, and other materials, illustrating the plasticity and yield behavior of these materials. It can model and simulate structures, such as linear tunnels, rock masses, or sheet-pile columns, which are surrounded by interacting soil or rock.

The FLAC also offers the ability to model and analyze the flow of groundwater and the processes of consolidation and stabilization by integrating these interactions with mechanical models. Additionally, this software can perform thermal calculations and creep-related computations, although these features may incur additional costs.

The following assumptions in Tables 1 and 2 were applied in the calculations used in this study to utilize the FLAC software.

Table 1 Static and dynamic young's modulus values at two specified depths

Parameters	Sections	Static	Dynamic
		Young's modulus (GPa)	Young's modulus (GPa)
Primary depth zone		36.03	66/82
Secondary depth zone		23/41	43/01

Table 2 Values of Internal Friction Angle and Cohesion

Parameters	Sections	Internal Friction	Cohesion
		Angle [degrees]	(MPa)
Primary depth zone		39/1	5/9
Secondary depth zone		39/1	5/9

Study area and time frame. The present study was conducted on a well drilled in the Marun oil field, located in Khuzestan Province, southwestern Iran, within the Dezful Embayment, one of the most prolific hydrocarbon provinces in the Middle East. The Marun oil field is geographically situated at approximately 31.4°-31.7° N latitude and 48.8°-49.1° E longitude and is characterized by a complex structural

setting associated with intense folding and faulting of the Zagros Basin²².

The reservoir interval investigated in this study corresponds to the Asmari Formation, which predominantly consists of limestone and dolomite and is known for extensive natural fracturing. Due to the presence of numerous fractures, the field has historically experienced severe losses from drilling fluids, making it a candidate for underbalanced drilling applications.

The research was carried out over a defined time period. Data collection and preliminary analysis were performed between March 2021 and June 2022, while numerical modeling, wellbore stability analysis, and result interpretation were conducted between July 2022 and December 2022. This time frame represents the complete duration of the research activities presented in this study.

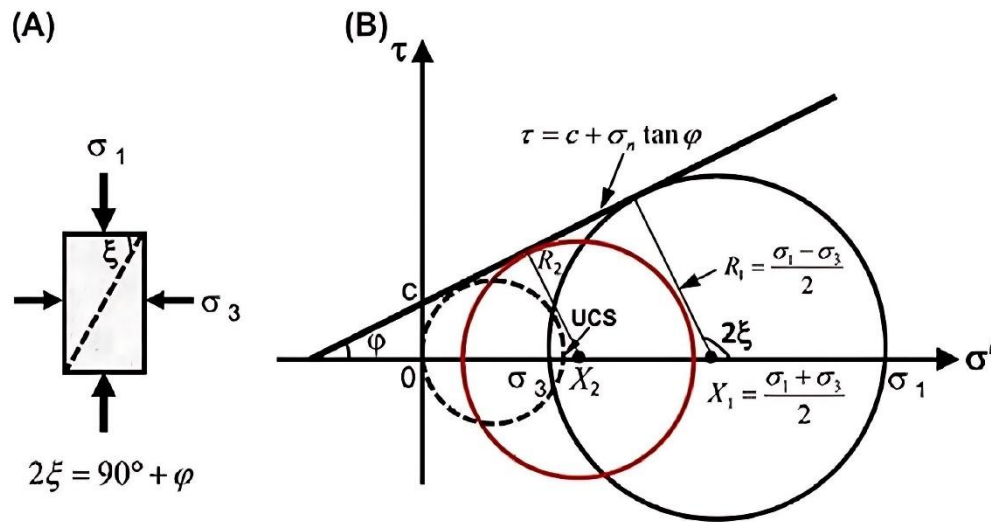


Figure 1 (a) Shear failure on the (a-b) plane; (b) Resistance envelope in shear and normal stresses²³

Utilization of the Mohr-Coulomb failure criterion

Determination of drilling mud window in vertical wells using the Mohr-Coulomb criterion. In 1776, Coulomb introduced the simplest and most important failure criteria. He stated that rock failure occurs when, under compression and pressure, the shear stress in the material on a specific plane (planes a-b in Figure a-1) reaches a sufficient level to overcome both the cohesion of the rock and the frictional force, which acts in the direction opposite to the movement of the failure plane. This criterion can be expressed

as²³.

$$\tau = c + \sigma_n \tan \varphi \quad (1)$$

In this equation, σ_n represents the normal stress acting on the failure plane (plane a-b in Figure 1), while cohesion and φ denote the rock's cohesion and internal friction angle, respectively (plane a-b in Figure b-1). This criterion illustrates the resistance to shear and normal stresses. In this failure criterion, the intermediate stress does not affect the shear and normal stresses, and it is assumed that the intermediate stress

is insignificant in the rock failure process. The Mohr-Coulomb failure criterion can also be expressed in terms of the maximum (σ_1) and minimum (σ_3) principal stresses²³.

$$\sigma_n = \frac{1}{2}(\sigma_1 + \sigma_3) + (\sigma_1 - \sigma_3)\cos 2\theta \quad (2)$$

$$\tau = \frac{1}{2}(\sigma_1 - \sigma_3)\sin 2\theta \quad (3)$$

The angle between the normal plane and direction of the maximum principal stress is shown in Figure a-1. This relationship is expressed as follows²³:

$$\theta = \frac{\pi}{4} + \frac{\phi}{2} \quad (4)$$

Angle ϕ can vary between 0° and 90° . However, the practical range of this angle was smaller (approximately 30°). Therefore, according to the above relation, θ can vary between 45° and 90° . It is important to note that ϕ has a constant value on the Mohr scale. Using equations (2) and (4), the Mohr-Coulomb criterion can be written as follows²³.

$$\sigma_1 = C_o + q\sigma_3 \quad (5)$$

In this relation, q is the slope of the line with respect to σ_1 and σ_3 , and its value is equal to²³.

$$q = \frac{1+\sin\phi}{1-\sin\phi} \quad (6)$$

C_o is the uniaxial compressive strength, which can be determined relative to the cohesion and internal friction angle of the rock²³.

$$q = \frac{2c \cos\phi}{1-\sin\phi} \quad (7)$$

Using Equations (5-7), we can determine the uniaxial tensile strength based on the cohesion of the rock (c) and the angle of internal friction (ϕ), as given in reference²³.

$$T_0 = \frac{2c \cos\phi}{1+\sin\phi} \quad (8)$$

The Mohr-Coulomb criterion can also be expressed in terms of the maximum shear stress τ_{max} and the effective mean stress²³.

$$T_0 = \frac{2c \cos\phi}{1 + \sin\phi} \quad (9)$$

As a result,

$$\sigma_{max} = \frac{1}{2}(\sigma_1 - \sigma_3) \quad (10)$$

$$\sigma_{m,2} = \frac{(\sigma_1 + \sigma_3)}{2} \quad (11)$$

This form of the Mohr-Coulomb criterion implies that an increase in the mean normal stress tends to prevent failure and that there is a linear correlation between the maximum shear stress and effective mean stress at failure.

A failure criterion is employed to determine the stress conditions under which wall collapse (compressive or shear failure) and crack formation (tensile failure) occur. In this section, the Mohr-Coulomb failure criterion, introduced in the previous chapter, is utilized for wellbore stability analysis²⁴.

$$\sigma_1 = USC + q\sigma_3 \quad (12)$$

$$q = [(\mu^2 + 1)^{\frac{1}{2}} + \mu]^2 = \tan^2\left(\frac{\pi}{4} + \frac{\phi}{2}\right) \quad (13)$$

Different modes of shear failure can occur in a wellbore depending on the relative magnitudes of the stresses surrounding the well. Typically, the most common mode of shear failure is characterized by $\sigma_\theta > \sigma_z > \sigma_r$, while the most common mode of tensile failure is characterized by $\sigma_r > \sigma_z > \sigma_\theta$ ²³.

In the case of shear failure, according to equation (12) and using the stress values and the considered stress regime, we will have: For example, if we assume the first case to be $\sigma_z > \sigma_\theta > \sigma_r$, then:

It is: $\sigma_r = \sigma_3$, $\sigma_\theta = \sigma_2$, $\sigma_z = \sigma_1$. By substituting the maximum and minimum stress values into the Mohr-Coulomb criterion and also using equation (13), we have:

$$P_{wb1} = \frac{B-UCS}{q} \quad (14)$$

Table 3 Shear failure modes and borehole breakout pressures based on the Mohr-Coulomb criterion²⁴

Failure Mode	Effective wellbore breakout pressure ($P_{w(BO)}$)
$\sigma_1 \geq \sigma_2 \geq \sigma_3$	$\frac{B-UCS}{q}$
$\sigma_z \geq \sigma_\theta \geq \sigma_r$	$\frac{A-UCS}{1+q}$
$\sigma_\theta \geq \sigma_z \geq \sigma_r$	$A-UCS-qB$

$$A = 3\sigma_H - \sigma_h, \sigma_r = P_w, \sigma_\theta = A - P_w, \sigma_z = B, B = \sigma_v + 2(\sigma_H - \sigma_h)$$

The same procedure applies to the next two shear stress cases, and the calculation results are (presented in Table 3)²⁴.

Furthermore, the Mohr-Coulomb criterion can be used to obtain the tensile failure stress. The failure stress in three other stress regimes is calculated as (summarized in Table 4)²⁴.

Table 4 Tensile Failure Modes and Borehole Breakout Pressures Based on the Mohr-Coulomb Criterion²⁴

$\sigma_1 \geq \sigma_2 \geq \sigma_3$	Effective wellbore fracturing pressure ($P_{w(fract)}$)
$\sigma_r \geq \sigma_\theta \geq \sigma_z$	$\frac{UCS + qE}{UCS + qD}$
$\sigma_r \geq \sigma_z \geq \sigma_\theta$	$\frac{1 + q}{UCS - E} + D$
$\sigma_z \geq \sigma_r \geq \sigma_\theta$	

We know that there is a tensile strength correction in the Mohr-Coulomb criterion. This tensile strength correction is defined based on the minimum principal stress and is in fact the same as the tensile failure criterion.

$$-T_0 = \sigma_3 \quad (15)$$

In the three mentioned cases of tensile failure, two cases arise for the minimum principal stress. In two cases, the tangential stress is equal to the minimum principal stress, and in one case, the axial stress of the well is equal to the minimum principal stress. In the first case mentioned in Table 4 ($\sigma_r \geq \sigma_\theta \geq \sigma_z$) in vertical wells, the axial stress is not a function of the mud pressure inside the well. Therefore, in vertical wells, it is assumed that only the tangential stress can become tensile and cause failure²³. Therefore:

$$P_w^{Frac} = 3\sigma_h - \sigma_H = T_0 \quad (16)$$

The calculated value is compared to Mohr-Coulomb results, and the lower value is set as the tensile hydraulic fracturing pressure and the upper mud window limit. For Drucker-Prager and modified Lade criteria, analytical solutions are complex, so numerical methods are required for mud window calculations. The Hoek-Brown criterion needs the coefficient m from triaxial tests and is thus not used here. Furthermore, since the Drucker-Prager criterion assumes equal compressive and tensile strength for the

rock, and this is a flaw in the criterion that affects the analysis results, the use of this failure criterion is also avoided. Therefore, the Mohr-Coulomb failure criterion, which is a common failure criterion in wellbore stability analysis, is used.

Mohr-Coulomb failure criterion in directional wellbore stability analysis. According to the Mohr-Coulomb failure criterion, the failure function is defined as follows:

$$F = c \cos\phi + \sin(\sigma_{m,2} - P_o) - T_{max} \quad (17)$$

In this case:

$$\tau_{max} = \frac{1}{2}(\sigma_1 - \sigma_3) \quad (18)$$

$$\tau_{m,2} = \frac{(\sigma_1 + \sigma_3)}{2} \quad (19)$$

According to the failure criteria presented in this section and the provided failure functions, failure will ensue when F is less than or equal to zero.

Directional wells require identifying an angular range around the wellbore where tensile stresses are present. While this angle is straightforward to determine in a vertical well, directional wells necessitate an iterative algorithm. This algorithm involves conducting stress analyses around the wellbore for angles ranging from the minimum to the maximum. The angles at which tensile stresses occur must be identified for subsequent analysis.

Numerical methods. By utilizing existing software and defining the geometry, boundary conditions, and strength and deformation properties of the rock mass accurately, acceptable designs can be achieved. Numerical methods allow for the modeling of surface and underground structures with any shape and cross-section, and the calculation of stresses and displacements at all desired points²⁵.

Using numerical methods, it is possible to analyze the drilling process, support, and the effect of water flow on the stability of rock and soil masses, including the stability of well walls²⁵.

Numerical methods are generally divided as follows:

Continuous Methods: i) Finite Element Methods. ii) Finite Difference Methods. iii) Boundary Element Methods (BEM)

Discrete Methods: i) Discrete Element Methods. ii) Discrete Fracture Network Methods. iii) Hybrid Methods. iv) Combinations like 81 FEM/DEM, BEM/DEM, or FEM/BEM. v). Other combinations of continuous and discrete methods²⁵.

Finite difference method. Is one of the oldest numerical methods for solving systems of differential equations and is still widely used in engineering problem-solving. Similar to the FEM, this method models the problem space as a continuum with elements connected at nodes. The advantage of the FDM is that it does not require a lot of computational power. Many researchers, including Wilkins in 1963, have shown that the results obtained from the FDM and the FEM are identical for specific problems, but the FDM is more flexible than the FEM. Among the most important software that use the FDM to solve geomechanical problems are FLAC2D and FLAC3D²⁵.

Results

Today, with the rapid advancement of computer science, the use of numerical methods for solving geotechnical problems has significantly expanded. Due to the high capabilities of numerical methods, it is possible to study and investigate the effects of discontinuities and inhomogeneities.

Numerical methods can have many applications in solving engineering problems. In the past, due to the lack of sufficient computational facilities and the time-consuming nature of calculations, empirical relationships were used more often. It should be noted that an accurate solution to geomechanical problems cannot be achieved solely through experimental or numerical methods. A combination of these two methods can help us solve complex earth problems. The basis of numerical methods is to transform a medium with infinite degrees of freedom into a medium with a limited number of degrees of freedom at a certain number of points in the medium. The position, number, and connectivity of these points are determined by meshing²⁵.

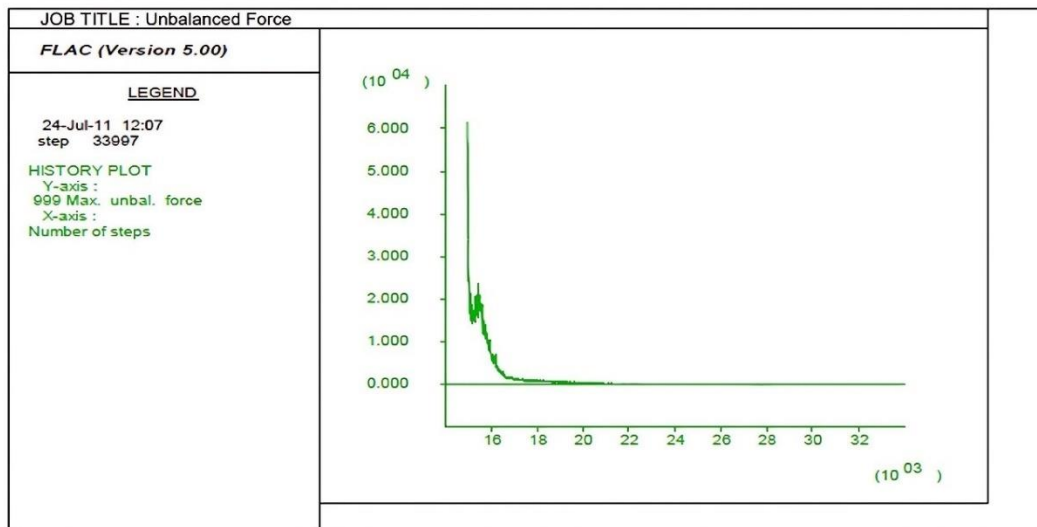


Figure 2 Diagram of unbalanced forces in a vertical well with minimum drilling mud pressure

FDM is one of the oldest numerical methods for solving systems of differential equations and is still

widely used in engineering problem-solving. Similar to the FEM, this method models the problem space

as a continuum with elements connected at nodes. The advantage of the FDM is that it does not require a lot of computational power. Many researchers, including Wilkins in 1963, have shown that the results obtained from the FDM and the FEM are identical for specific problems, but the FDM is more flexible than the FEM. Among the most important software that use the FDM to solve geomechanical problems

are FLAC2D and FLAC3D²⁵. Those powerful tools can be applied to determine the mud window and will be described in the following.

Vertical modeling to determine the lower limit of the mud window in the vertical section of the well. In Figure 2, the diagram of unbalanced forces for the vertical well model, which approaches zero, indicating the stability of the model, is shown.

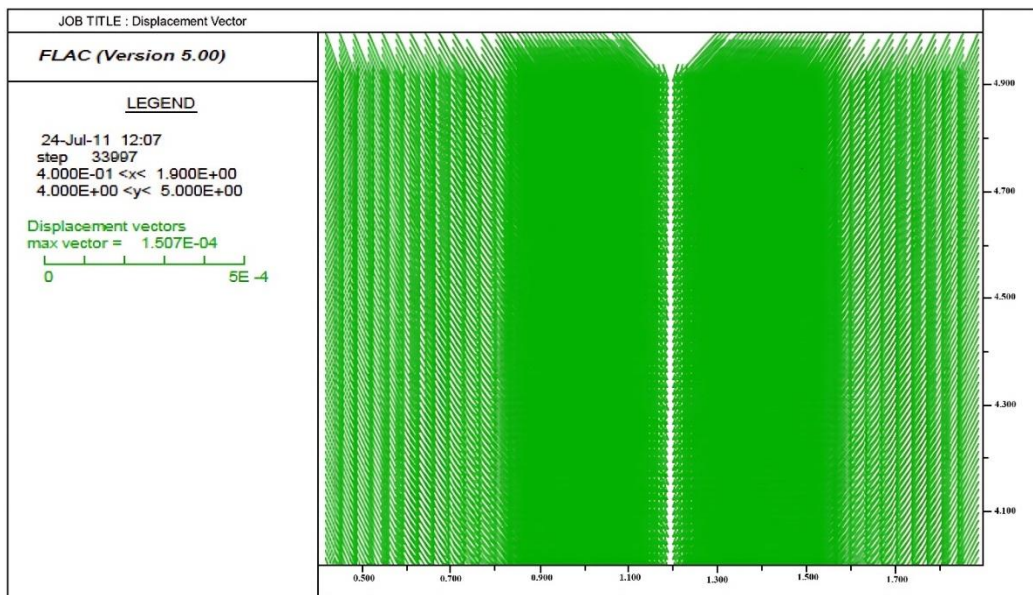


Figure 3 Displacement Field Around the Well

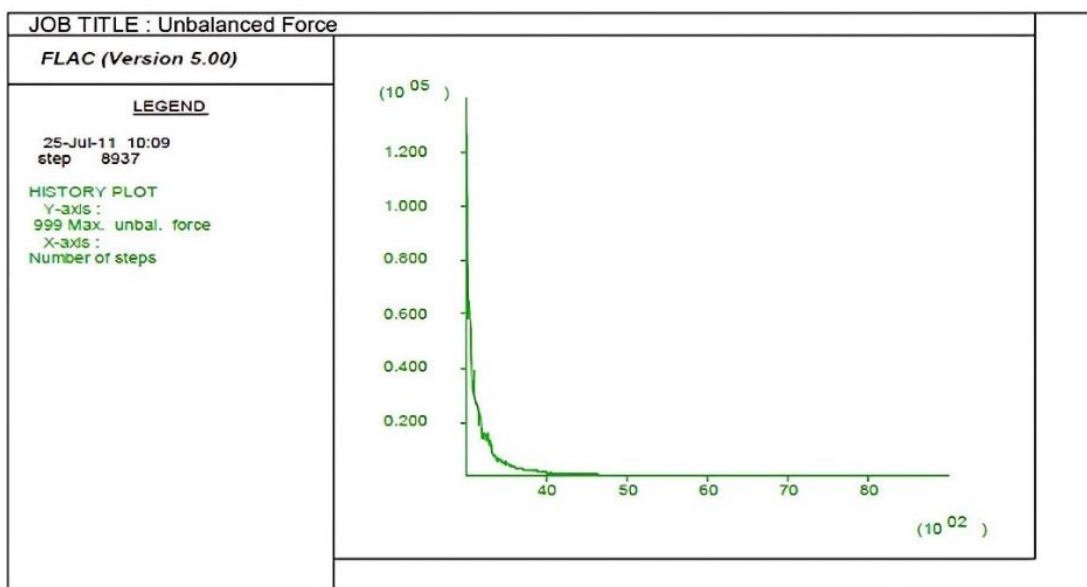


Figure 4 Diagram of unbalanced forces in the horizontal model of a vertical well under maximum drilling mud pressure

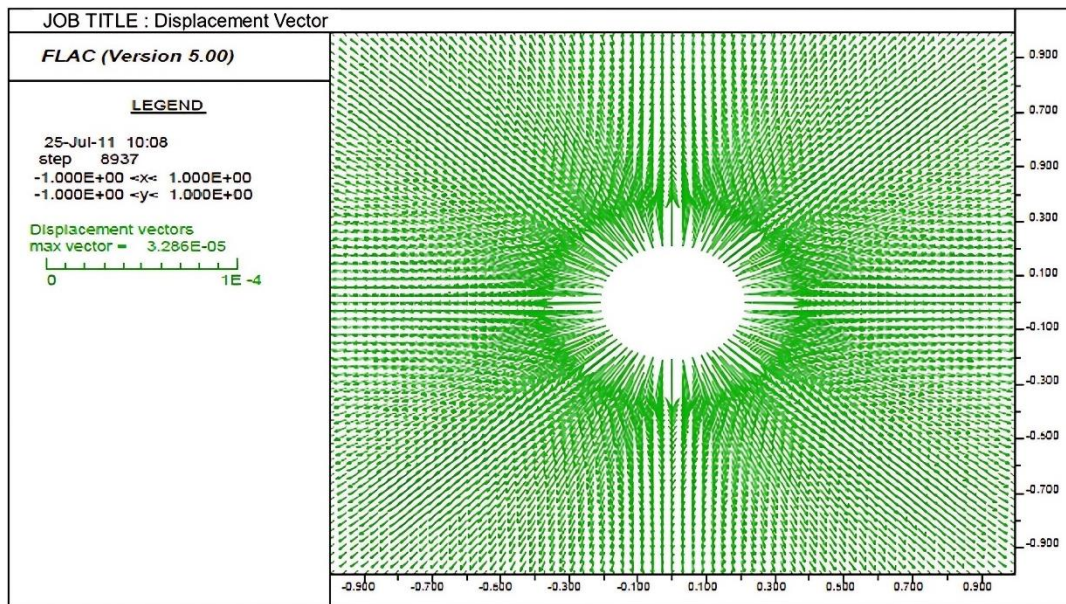


Figure 5 Displacement Diagram for Maximum Mud Pressure Condition

Figure 3 shows the displacement vector (field) around the wellbore, with a maximum value of 0.15 mm, which is within the allowable displacement limits.

Horizontal modeling for determining the upper limit of the mud window in the vertical section of the well.

Figure 4 shows the diagram of unbalanced forces in the horizontal model of a vertical well under maximum drilling mud pressure. Figure 5 shows the diagram of displacements caused by maximum drilling mud pressure, which has led to wellbore wall divergence.

Based on the results obtained from numerical modeling in both vertical and horizontal conditions in the vertical section of the well using the underbalanced drilling technique: i) The safe lower limit of the mud window is determined to prevent wellbore collapse. ii) By applying the underbalanced drilling technique in the well, the lowest mud pressure that prevents wellbore collapse is established. iii) Given the higher pore pressure, the formation fluid flows into the well,

and this formation fluid must be transferred to the surface by the returning mud flow.

Later, different well deviation angles will be analyzed and will compare with the perfectly vertical ones.

Modeling to determine the lower limit of the mud window at a 60-degree deviation angle. In this part, the mud window prevents the creation of shear, and tensile fractures around the well will be regulated. Hence, the mud window is determined for the deviated section of the well with a 60-degree deviation from the vertical. The considered depth section in this part is between 2150 and 2155 m, which is located in the deviated part of the well.

Figure 6 shows the diagram of unbalanced forces in a deviated well with a 60-degree angle under minimum drilling mud pressure. This diagram indicates that the unbalanced forces have reached a state of stability. Figure 7 shows the diagram of displacement vectors (fields) around the well at a minimum fluid pressure of 48 MPa. Based on the results, the mini-

minimum pressure that can prevent wellbore collapse is 47 MPa.

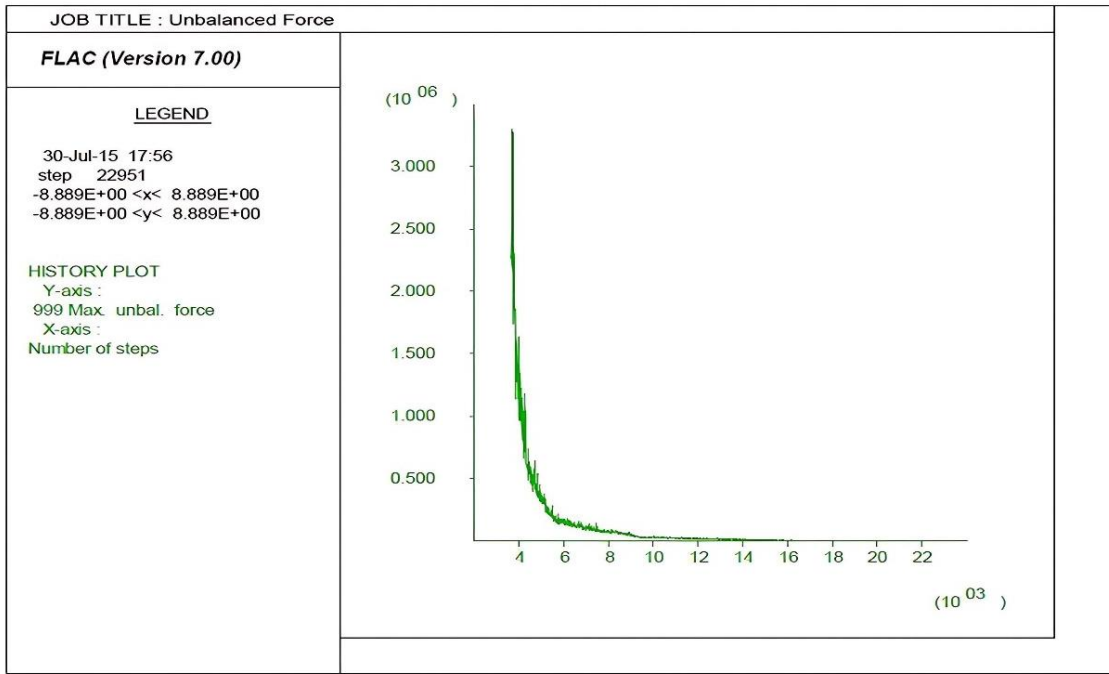


Figure 6 Diagram of unbalanced forces in the vertical model of a deviated well under minimum drilling mud pressure

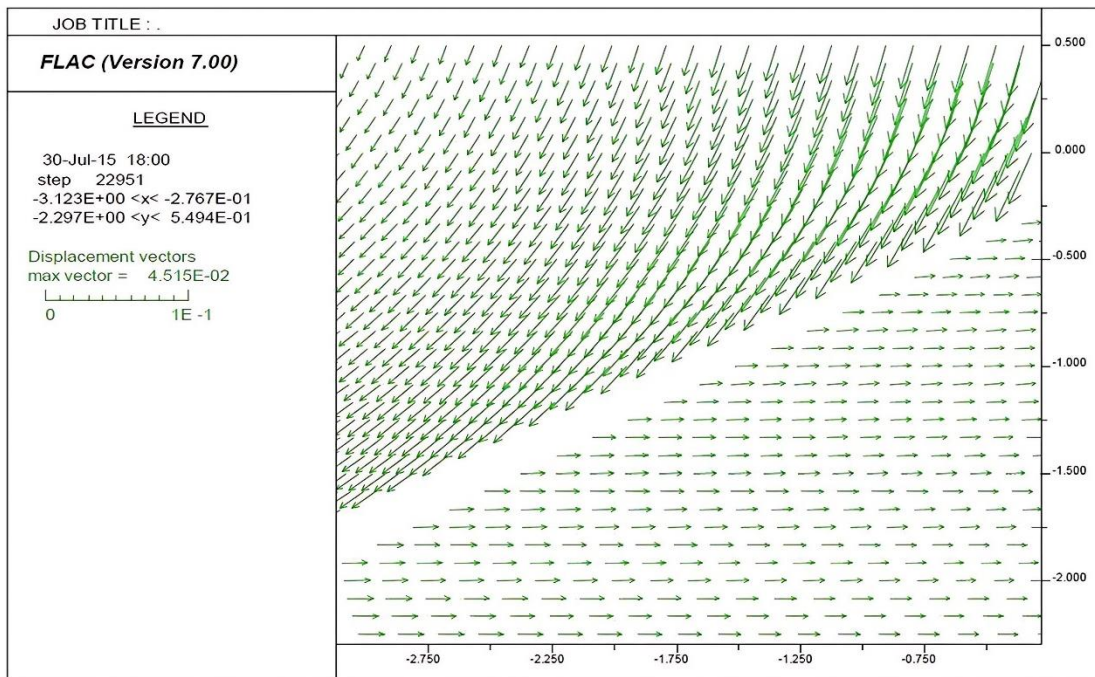


Figure 7 Diagram of displacements in the deviated well under minimum drilling mud pressure

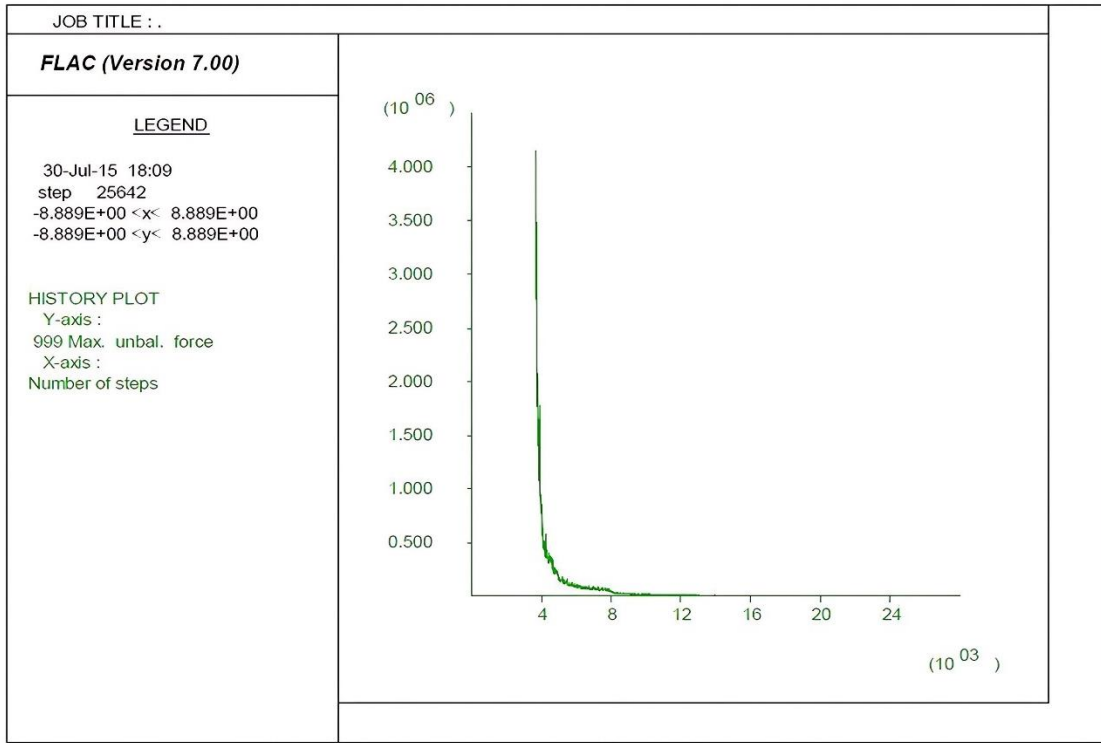


Figure 8 Diagram of unbalanced forces in the horizontal model of a deviated well under maximum drilling mud pressure

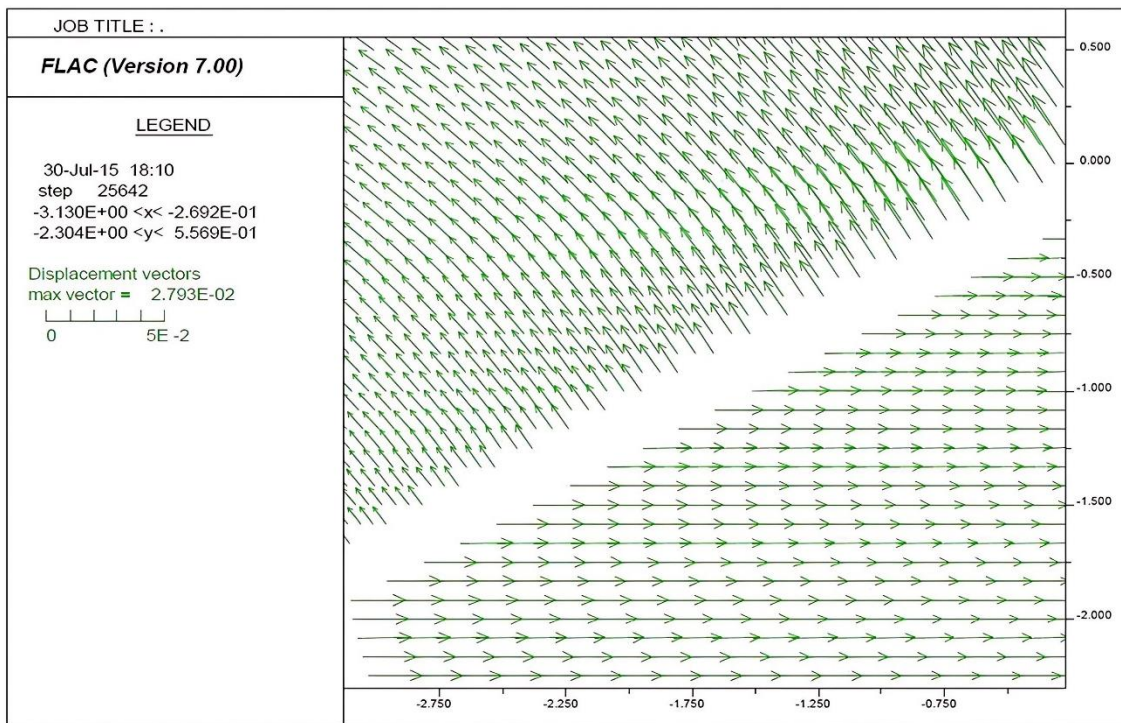


Figure 9 Diagram of displacements in the deviated well under maximum drilling mud pressure

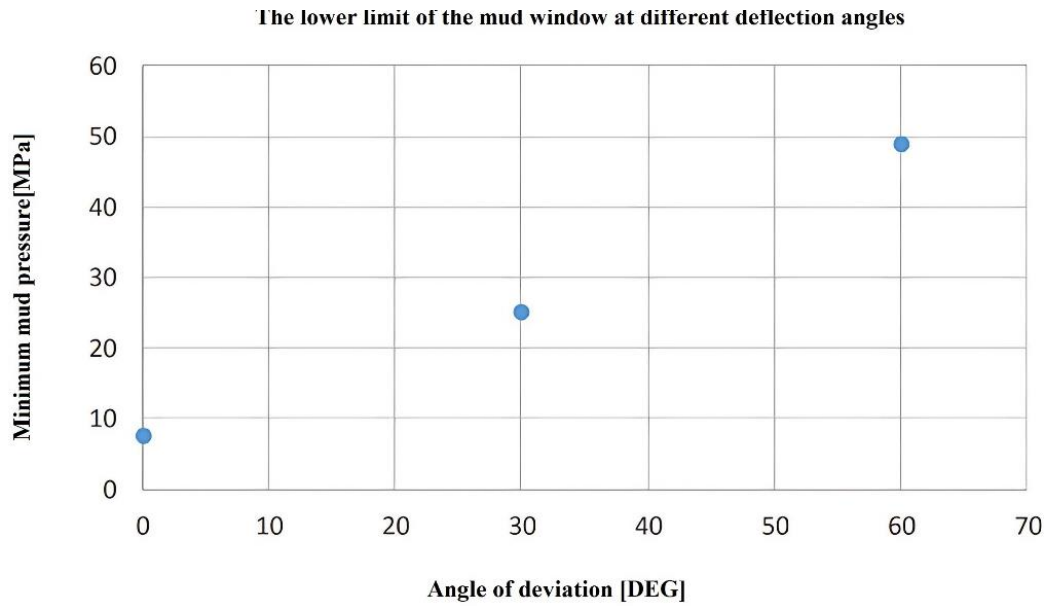


Figure 10 Diagram showing the relationship between deviation angles and minimum mud weight

Modeling to determine the upper limit of the mud window at a 60-degree deviation angle. Figure 8 shows the upper limit of the mud window, determined through numerical modeling at a 60-degree deviation angle from the vertical, to prevent hydraulic fracturing. Figure 9 shows the displacements around the wellbore caused by the maximum drilling mud pressure for the hydraulic fracture case.

Selecting the most stable deviation angle for wellbore drilling. In this section, the impact of the wellbore deviation angle on its stability is investigated. The main objective was to determine the optimal deflection angle that minimizes the probability of shear failures. To achieve this, a model was developed using FLAC software. In this model, the wellbore deviation angles were varied, and a plot of the lower limit of mud weight for different deviation angles was generated. The point with the lowest predicted shear failure pressure is identified as the optimal deviation angle. Consequently, the greater the number of deviation angles considered, the higher the accuracy and the more reliable the prediction for the wellbore trajectory. To assess the impact of different de-

viation angles on wellbore stability using numerical methods, a study was conducted at a depth of 2152.5 m, where the well had encountered stability issues. Since the variations in mechanical properties of the formation and in-situ stresses within this interval are minimal, average values for this zone were used in the analysis.

Figure 10 illustrates the minimum mud weight determined by numerical modeling for deviation angles of 0, 30, and 60 degrees to examine the effect of deviation on wellbore stability. Figure 10 clearly shows that as the deviation angle increases from the vertical, the required mud weight to maintain wellbore stability and prevent shear failure, and consequently, wellbore collapse, also increases. Therefore, as the deviation angle increases, the well becomes less stable. The optimal deviation angle for drilling using the underbalanced drilling method in this well is 0 degrees (vertical well). However, if deviated drilling with an underbalanced method is desired, the most suitable deviation angle is 30 degrees. A horizontal well will be unstable under any mud pressure.

Discussion

Determination of the Mud Window at Deviation An-

gles of 30 and 90 Degrees. Figures 11 and 12 are related to the lower limit of the mud window at a 30-degree deviation angle.

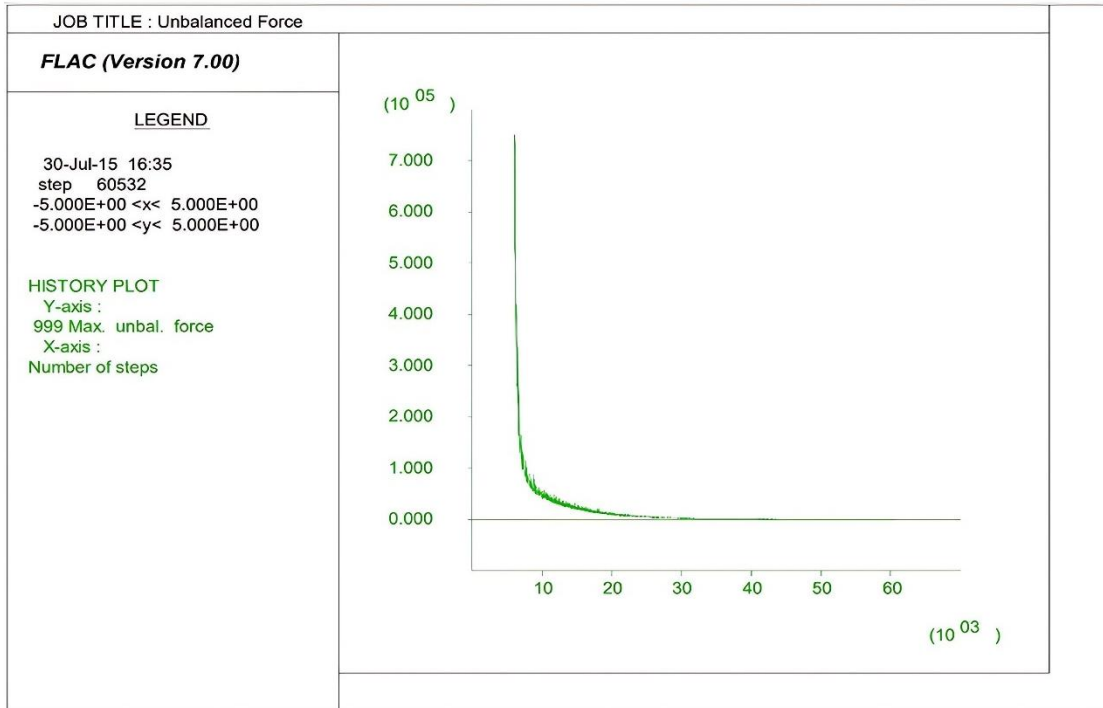


Figure 11 Diagram of unbalanced forces for evaluating the stability of the created model

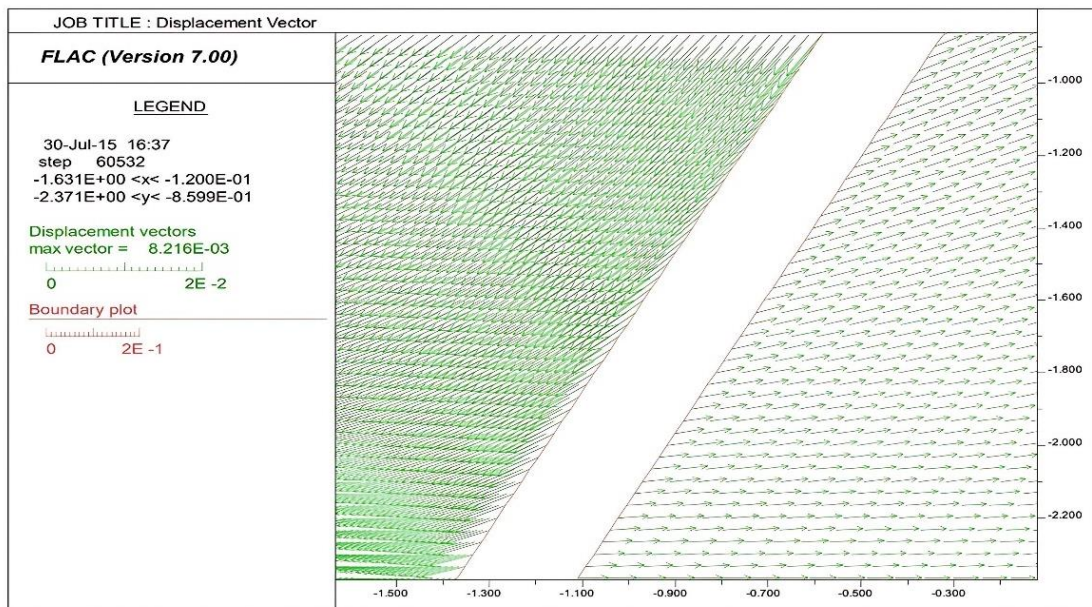


Figure 12 Diagram of displacements around the well at minimum drilling mud pressure

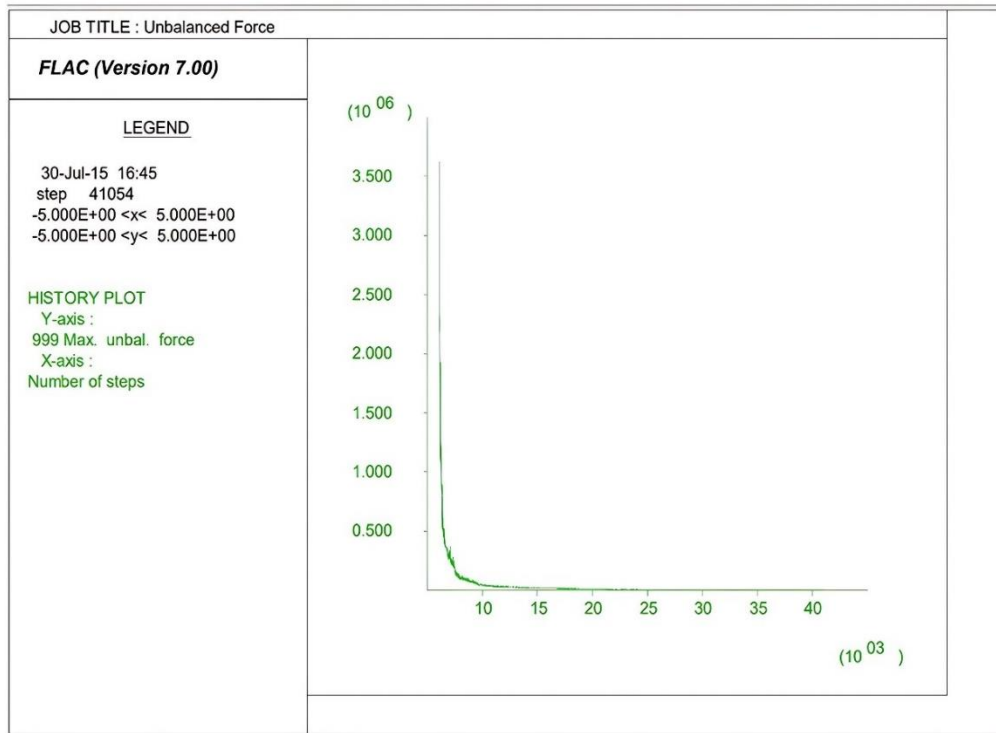


Figure 13 Diagram of unbalanced forces in the well under maximum drilling mud pressure

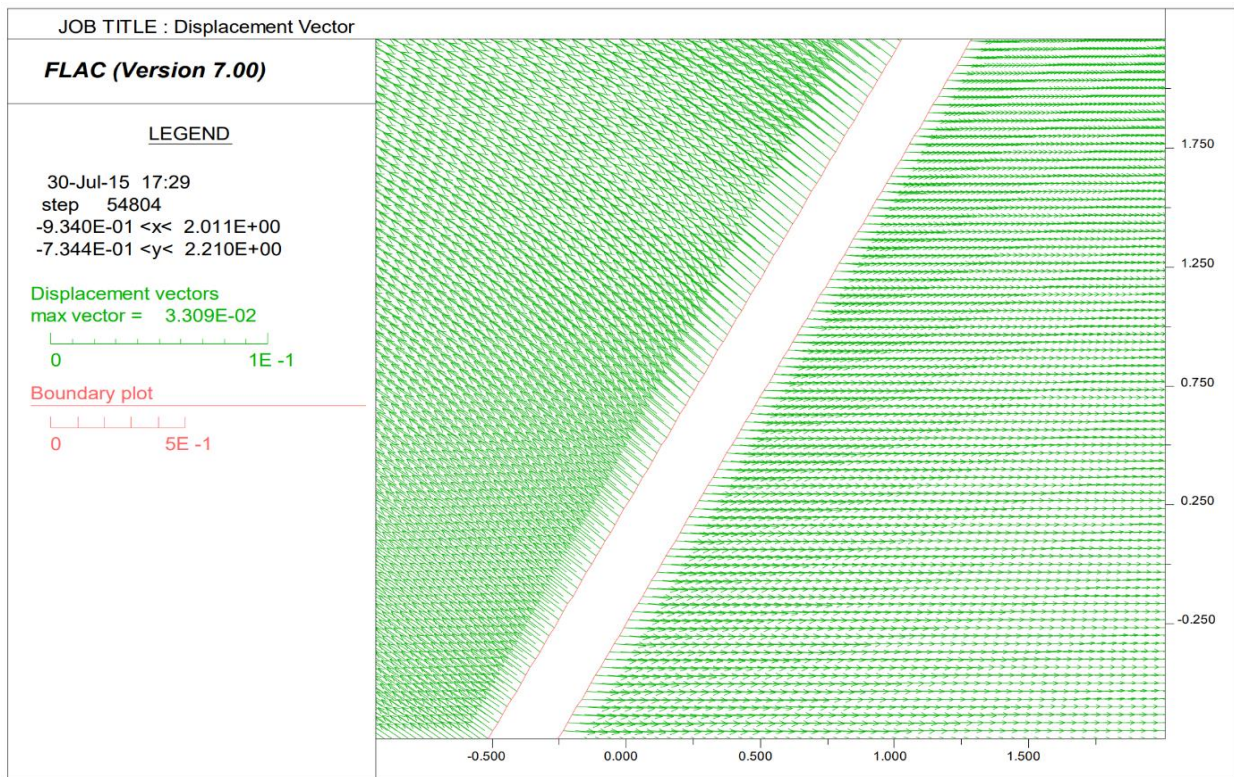


Figure 14 Diagram of displacement vectors around the well under maximum drilling mud pressure

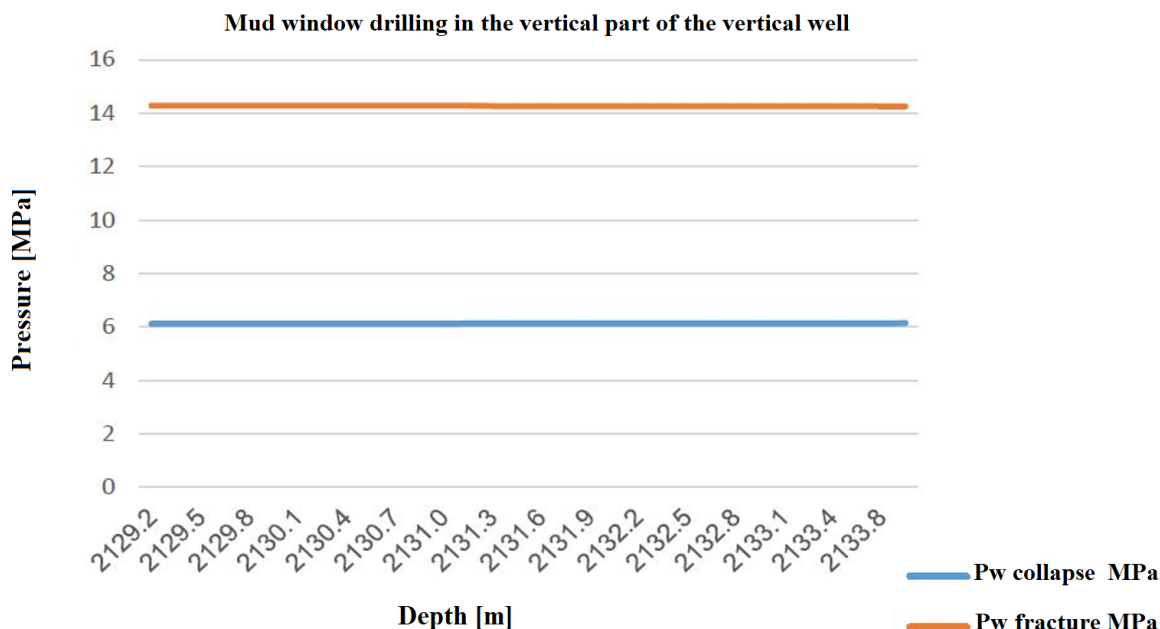


Figure 15 Safe mud weight window for the well using the Mohr-Coulomb criterion

Figures 13 and 14 are related to the upper limit of the mud window at a 30-degree deviation angle. Based on the above diagrams, the determined mud windows are as Table 5. Based on the results of the numerical

modeling, horizontal drilling, whether using under-balanced or overbalanced drilling methods, is not feasible due to the significant difference between horizontal and vertical stresses.

Table 5 Results of the mud windows determined at deviation angles of 30 degrees and 90

Mud window	Deviation angle	Lower Limit of Mud Window (Megapascals)	Upper Limit of Mud Window (Megapascals)
Deviation Angle: 30 Degrees		25	85
Deviation Angle: 90 Degrees		Unstable at Any Pressure	Unstable at Any Pressure

Design of the drilling fluid window in the vertical section of the well using the Mohr-Coulomb failure criterion. The equations for calculating the safe mud weight window for a vertical well using the Mohr-Coulomb failure criterion are presented in Tables 3 and 4. Since the Mohr-Coulomb failure criterion overestimates the tensile strength of the rock, the equation presented in equation (16) is used to calculate the upper limit of the safe mud weight. The drill-

ing fluid window for one of the wells in the Marun oil field, calculated using the Mohr-Coulomb criterion, is shown in Figure 15.

It is observed that the Mohr-Coulomb failure criterion determines a lower limit of 5.9 MPa and an upper limit of 14.4 MPa for the safe mud weight. These values are quite close to the values obtained from the numerical wellbore modelling.

Comparison of numerical analysis results and ana-

lytical methods. The minimum and maximum mud window pressures in the vertical section of the well were determined to be 5.9 and 14.4 MPa, respectively, using the Mohr-Coulomb failure criterion. These values are close to the minimum and maximum mud window pressures determined by the numerical method, which were 7.5 and 15.7 MPa, respectively. However, the Mohr-Coulomb failure criterion predicts a maximum mud window pressure that is lower than the pore pressure, which could lead to fluid influx from the formation into the well if the mud weight is based on the Mohr-Coulomb criterion. In other words, the well would be drilled underbalanced. The numerical method, on the other hand, predicts a maximum mud window pressure that is slightly higher than the pore pressure, ensuring that

there would be no fluid influx if the mud weight is less than the maximum predicted pressure. In practice, due to the proximity of the pore pressure to the formation fracture pressure, determining the mud weight between these two pressures can be challenging, as exceeding the formation fracture pressure can lead to hydraulic fracturing. The numerical method also suggests that underbalanced drilling is the most suitable method for this well. In the deviated section of the well, due to the complexity and time-consuming nature of using analytical methods to determine the mud window, only the numerical method was used. Comparison of numerical method results with Mohr-Coulomb failure criterion in the vertical section of the well is shown in Table 6.

Table 6 Comparison of numerical method results with Mohr-Coulomb failure criterion in the vertical section of the well

Values Methods	Maximum Mud Weight Corresponding to Pressure (pounds per gallon)	Minimum Mud Weight Corresponding to Pressure (pounds per gallon)	Maximum Pressure (MPa)	Minimum Pressure (MPa)
Numerical Modeling	6.2	3	15.7	7.5
Mohr-Coulomb Criterion	5.6	2.4	14.4	5.6

Wall instability is one of the most significant challenges in drilling operations. Although numerous measures have been taken to address this issue, determining the safe mud weight remains the most effective control method. This requires a thorough understanding of the mechanical properties of the formation. The more information available about the mechanical properties of the rock and its behavior under stress, the more accurate and safer the mud window can be. By determining the mud window, the most critical drilling problems, such as fluid influx into the well and wall collapse, can be controlled. If these problems occur, they can pose significant financial and safety risks to the drilling rig and personnel. This research aimed to investigate the effect of

well deviation on stability and the range of mud weight. The following conclusions were drawn from the investigations and calculations that were conducted.

Based on the pore pressure values and the upper and lower limits of the suitable drilling fluid density, underbalanced drilling is the most appropriate technique for the vertical section of the well. However, in the deviated section, due to the disturbed stress distribution and the increased collapse pressure, it is not feasible to drill underbalanced. As the deviation angle increases, the well becomes more unstable, and the collapse pressure required to stabilize the well increases.

The results of this study indicate that the numerical

method can provide a more accurate range for the lower and upper limits of the drilling fluid density compared to the analytical process. Additionally, as the deviation angle increases from the vertical, the collapse pressure also increases, consequently requiring a higher drilling fluid density to prevent wall collapse. According to the results, the Mohr-Coulomb failure criterion provides a reasonable estimate of the safe mud weight window required for wellbore stability, similar to the numerical results.

In addition, studies have pointed out that drilling at a 90-degree deflection angle (horizontal well) is not feasible due to the significant difference between horizontal and vertical stresses, regardless of whether underbalanced or overbalanced drilling is used.

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Conflicts of interest

The authors declare that they have no competing interest.

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Ethical considerations

This article is derived from a doctoral dissertation in petroleum engineering at Islamic Azad University

Science and Research Branch, titled " Investigating the effect of wellbore deviation on its stability in carbonate formations (Water-based drilling fluid)" Since it does not involve living beings (humans or animals), it is not subject to ethical review. The terms established by the University for the development of this type of research have been respected.

Limitations in the research

This study faced limitations due to the lack of information on high temperature and high pressure (HPHT)wells.

Authors' contribution to the article

All authors, read and approved the final manuscript.

Permissions for publication

It does not require.

Access to data

All data generated or analyzed during this study are included in this published article.

Use of artificial intelligence

We assume that the entire document was written based on ethical and professional criteria, and AI was not used to make the figures or text.

Cited Literature

1. Chen W, Chen Y, Gabaldon O, Montes O, Ashok P, Yi M, et al. Enhancing offshore drilling safety:

- identification and integration of leading indicators for loss of offshore well control. *SPE Journal* 2026;31(01):280-97. DOI: <https://doi.org/10.4043/35818-MS>
2. Cheatham Jr JB. Wellbore stability. *J Pet Technol* 1984;36(06):889-96. DOI: <https://doi.org/10.2118/13340-PA>
 3. Borujeni FG, Hamad MS, Shahi AS. Coupled hydraulic-geomechanical analysis in well drilling operations: a systematic review of experimental and numerical methodologies. *Carbonates Evaporites* 2026;41:13. DOI: <https://doi.org/10.1007/s13146-025-01215-9>
 4. Ruzhnikov A. Optimizing drilling performance and accelerating learning curve in unconventional reservoir development. In: *SPE/IADC Middle East Drilling Technology Conference and Exhibition, SPE 2025* [Internet]. Abu Dhabi, UAE. Richardson (TX): Society of Petroleum Engineers; 2025. Paper SPE-225762-MS. DOI: <https://doi.org/10.2118/225762-MS>
 5. Edan BK, Hussein HAA. Geomechanics analysis of well drilling instability: A review. *J Eng* 2023; 29(08):94-105. DOI: <https://doi.org/10.31026/j.eng.2023.08.07>
 6. Liu W, Chen Z, Li A, Zhu X. The mechanism of wellbore instability in hot dry rock formations under 3D in-situ stresses. *Geoenergy Sci Eng* 2026; 256:214147. DOI: <https://doi.org/10.1016/j.geoen.2025.214147>
 7. Haris Q, Sahir I, Zulfiqar A, Sana-Ul-Hussnain S, Ibtihaj A, Mudassir K, et al. Successful underbalanced well completion operations in depleted carbonate reservoir of brown gas field a case study. In: *Abu Dhabi International Petroleum Exhibition and Conference, SPE 2024* [Internet]. Abu Dhabi, UAE. Richardson (TX): Society of Petroleum Engineers; 2024. Paper SPE-222115-MS. DOI: <https://doi.org/10.2118/222115-MS>
 8. Al-Sharea MF. The value of underbalanced coiled tubing drilling (UBCTD) in unconventional mature fields: decision analytic approach. In: *International Conference and Exhibition on Formation Damage Control, SPE 2024* [Internet]. Lafayette, Louisiana, USA. Richardson (TX): Society of Petroleum Engineers; 2024. Paper SPE-217890-MS DOI: <https://doi.org/10.2118/217890-MS>
 9. Elrayah AAI. Enhancing drilling operations: prioritizing wellbore integrity, formation preservation, and effective mud waste control (case study). *J Eng Appl Sci* 2024;71:86. DOI: <https://doi.org/10.1186/s44147-024-00383-0>
 10. Mozaffari S, Rahmani O, Piroozian A, Ziabakhsh-Ganji Z, Mostafavi H. Oil-well lightweight cement slurry for improving compressive strength and hydration rate in low-temperature conditions. *Constr Build Mater* 2022;357:129301. DOI: <https://doi.org/10.1016/j.conbuildmat.2022.129301>
 11. Hoseinpour M, Riahi MA. Determination of the mud weight window, optimum drilling trajectory, and wellbore stability using geomechanical parameters in one of the Iranian hydrocarbon reservoirs. *J Petrol Explor Prod Technol* 2022;12:63-82. DOI: <https://doi.org/10.1007/s13202-021-01399-5>
 12. Fang C, Wang Q, Jiang H, Chen Z, Wang Y, Zhai W, et al. Shale wellbore stability and well trajectory optimization: a case study from Changning, Sichuan, China. *Petrol Sci Technol* 2023;41(5): 564-85. DOI: <https://doi.org/10.1080/10916466.2022.2092132>
 13. Li X, Zhang C, Feng Y, Wei Y, Chen X, Weng H, et al. An integrated geomechanics approach to evaluate and manage wellbore stability in a deep graben formation in Tarim Basin. *J Pet Sci Eng* 2022;208(Pt A):109391. DOI: <https://doi.org/10.1016/j.petrol.2021.109391>

14. Nwonodi RI, Okoro EE, Dosunmu A. Handling narrow margin and drilling problems in deepwater using geomechanics, well design, and process management. *Geoenergy Sci Eng* 2025;256:214173. DOI: <https://doi.org/10.1016/j.geoen.2025.214173>
15. Shahrekordi AP, Behnood M, Hosseinian A, Mozaffari S, Sheikhzakariaee SJ. A sensitivity analysis for the effective parameters disparity on pressure and pressure derivative of well-testing in a horizontal well. *Pet Coal* 2019;61(4):749-56.
16. Zhou Y, Zhang H, Wu Y, Li X, Xi C, Lv K, et al. Mechanism of wellbore instability considering tubular-string contact with the wellbore wall. *Sci Rep* 2025;15(1):26375. DOI: <https://doi.org/10.1038/s41598-025-10714-7>. PMID: 40691189; PMCID: PMC12280116.
17. Guo J, She C, Liu H, Cui S. Rock mechanical properties and wellbore stability of fractured dolomite formations. *ACS Omega* 2023;8(38):35152-66. DOI: <https://doi.org/10.1021/acsomega.3c04768>. PMID: 37779954; PMCID: PMC10536088.
18. Alomairi MRR, Rahimi M. Geomechanical modeling for determining safe mud window and evaluating wellbore wall stability using numerical simulation: A case study. *J Solid Mech* 2024;16(3):314-36. DOI: <https://doi.org/10.60664/jsm.2024.1122691>
19. Najibi AR, Ghafouri M, Lashkaripour GR, Asef MR. Reservoir geomechanical modeling: In-situ stress, pore pressure, and mud design. *J Pet Sci Eng* 2017;151:31-9. DOI: <https://doi.org/10.1016/j.petrol.2017.01.045>
20. Taleghani AD, Gonzalez M, Shojaei A. Overview of numerical models for interactions between hydraulic fractures and natural fractures: Challenges and limitations. *Comput Geotech* 2016;71:361-8. DOI: <https://doi.org/10.1016/j.compgeo.2015.09.009>
21. Ismail A, Azadbakht S. A comprehensive review of numerical simulation methods for hydraulic fracturing. *Int J Numer Anal Methods Geomech* 2024;48(5):1433-59. DOI: <https://doi.org/10.1002/nag.3689>
22. Alavi M. Regional stratigraphy of the Zagros fold-thrust belt of Iran and its proforeland evolution. *Am J Sci* 2004;304(1):1-20. DOI: <https://doi.org/10.2475/ajs.304.1.1>
23. Bell JS, Gough DI. Northeast-southwest compressive stress in Alberta evidence from oil wells. *Earth Planet Sci Lett* 1979;45(2):475-82. DOI: [https://doi.org/10.1016/0012-821X\(79\)90146-8](https://doi.org/10.1016/0012-821X(79)90146-8)
24. Motahari M, Hashemi A, Molaghab A. Successful mechanical earth model construction and wellbore stability analysis using elastic and plasticity solutions, a case study. *Geomech Energy Environ* 2022;32:100357. DOI: <https://doi.org/10.1016/j.gete.2022.100357>
25. Chandrasekaran S, Selvakumar NM. Dynamic analysis of drillship under critical environmental loads. In: *Proceedings of the 33rd International Ocean and Polar Engineering Conference; 2023 Jun; Ottawa, Canada*. Richardson (TX): International Society of Offshore and Polar Engineers; 2023. [cited May 3, 2025]. Paper Number: ISOPE-I-23-342. Retrieved from: <https://onepetro.org/ISOPEIOPEC/proceedings-abstract/ISOPE23/ISOPE23/ISOPE-I-23-342/524728>

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