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Time Dependent Mechanical Borehole Stability Analysis Using PBORE-3D

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Abstract*- Borehole instability, commonly referred to as 'tight hole' or 'stuck pipe', can either be mechanical or chemical depending on the source of the problem. Mechanical borehole instability occurs as soon as the new formation is drilled due to either too low or too high mud weight compared to in-situ rock strength. Due to consolidation effect, a time dependent mechanical borehole stability analysis needs to be performed if the borehole is left open for a period of time. A poromechanics stability simulator, PBORE-3D, is used for time dependent mechanical borehole stability analysis of a virtual 12 ¼" horizontal borehole drilled in Eocene shale, Cardium sandstone and Cardium interbedded sandstone/shale using modified Lade criterion.*

Drilling at near balanced condition in Eocene shale (isotropic in-situ horizontal stress) will initially produce collapse region around the borehole which does not increase much with time. A horizontal borehole drilled in the direction of minimum horizontal stress in Cardium sandstone (anisotropic in-situ horizontal stress) is found more stable than that drilled in the maximum horizontal stress direction for near balanced drilling condition. The stable mud window for Cardium interbedded sandstone/shale is observed not to change appreciably with time for a horizontal well drilled in the direction of minimum principal horizontal stress.

Based on the analysis results, a horizontal borehole drilled in the direction of minimum horizontal stress (for an anisotropic horizontal stress field) with near balanced drilling condition is found mechanically more stable than that drilled overbalanced.

Keywords: Mechanical borehole stability, Consolidation, PBORE-3D, Near balanced drilling condition

1. INTRODUCTION

Wellbore instability is the major cause of nonproductive time during drilling operation[1] and hence a major concern during drilling. It costs the petroleum industry more than six billion USD worldwide every year[1]. Therefore, the petroleum industry is keen to improve their understanding of borehole instability.

The formation at a given depth is subjected to three in-situ principal stresses – one vertical stress and two horizontal stresses. When a borehole is drilled, the surrounding rock needs to carry the load which was previously carried by the removed rock. This causes stress redistribution in the vicinity of the borehole. The surrounding rock will fail, if the redistributed stress state exceeds the rock strength.

Borehole instability leads to operational problems, such as 'tight hole' or 'stuck pipe'. Mostly encountered in shale and mudstone[2], borehole instability related incidents result in loss of time (and occasionally equipment) which account for at least 10% of the drilling costs[3].

Wellbore instability can either be mechanical or chemical depending on the source of the problem[4]. Mechanical instability occurs due to either too low or too high mud weight compared to the rock strength. On the other hand, chemical instability (also referred to as shale instability) is time dependent and most commonly associated with water adsorption in shaly formations. Even though a number of instances are observed where both mechanical and chemical instabilities occur in combination, mechanical wellbore instability is found to dominate over chemical borehole instability during the drilling phase of operations[5].

According to Fjær et al[2], there are four sources of time delayed borehole failure- consolidation, temperature (mud cooling), creep and, chemical interaction between the mud and the formation[2]. Consolidation is related to a transient process by which pore pressure equilibrium is re-established after a change in the in-situ stress state caused by drillout. The thermal effect is proportional to rock stiffness and is observed to improve borehole stability if the mud is colder than the formation. Creep, a time dependent failure mechanism of material under constant load level beyond the yield strength, occurs in the borehole if the mud weight is kept marginally above the lower limit (collapse) for long enough time. With increasing temperature, the risk of accelerating creep rates increases. Chemical interaction between the mud and the formation leads to time dependent chemical instability which is mostly encountered while drilling through shale, the most vulnerable but unavoidable cap rock. In this paper, only the time-dependent mechanical aspect of borehole instability caused by consolidation is considered.

Simulation results for a 12-1/4” horizontal hole obtained using a poromechanics simulator, PBORE-3D; based on published mechanical properties of Ecoene shale, Cardium sandstone and Cardium interbedded sandstone/shale are presented in the current paper. Based on the simulation results, a stable drilling direction for this horizontal borehole is suggested along with prescribed drilling conditions.

2. MECHANICAL WELLBORE INSTABILITY

On the basis of failure mechanism, mechanical wellbore instability can be classified as shear (also called collapse) and tensile failure. These failures occur due to stress concentration around the borehole. The rock will fail once the stress state exceeds the shear strength or the tensile strength of the rock.

In order to describe the redistributed stress state (produced due to drillout), three normal stresses (radial stress, axial stress and tangential or hoop stress) are used. The hoop stress is significant in predicting collapse and hydraulic fracture. This stress is maximum in the minimum horizontal stress direction and minimum in the maximum horizontal stress direction for a vertical wellbore. If the wellbore pressure is too high, hoop stress will be tensile and hydraulic fracture will occur if the tensile strength of the rock (which is assumed to be zero in most cases due to existence of fracture in the rock) is exceeded. On the other hand, if the wellbore pressure is too low, the wellbore will collapse due to shear failure. Figure 1 shows both failure modes along with the consequences. Hydraulic fracture will result in mud loss, while compressive failure will produce breakouts. Fracture will appear in the direction of maximum horizontal stress and breakouts will appear in the direction of minimum horizontal stress.

For a borehole drilled in a general direction, breakouts will appear in the σ_3 direction and tensile fractures will appear in the σ_1 direction.

To be noted that the shear failures most critical to the stability of a borehole are failures where either the hoop stress or the axial stress along the borehole axis is the maximum and the radial stress is the minimum[3].

In addition, blade-shaped cavings can be produced when the well pressure is lower than the pore pressure. This occurs as the effective radial stress becomes tensile. This failure mode is called spalling[3].

To manage mechanically-induced wellbore instability, it is necessary to determine critical mud weights that will provide sufficient wellbore wall support to counteract the redistribution of stresses caused by drillout. The critical mud weights depend on the in-situ stress regime, pore pressure, wellbore azimuth and inclination, formation properties and drainage conditions[5]. Different shear failure criteria are used to determine critical mud weights.

2.1 Shear Failure Criteria

A shear failure criterion has the following general form:

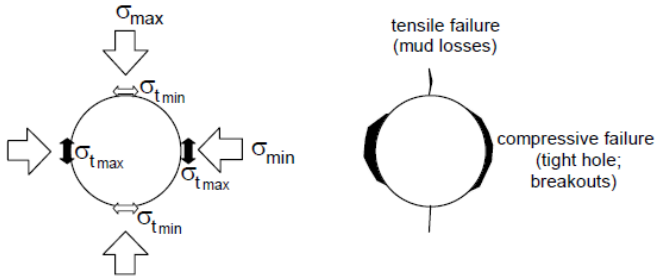

Fig.1: Tensile and shear failure for a vertical borehole[6]

$$\sigma_1 = f(\sigma_2, \sigma_3)$$

Typically available shear failure criteria are Mohr-Coulomb, Hoek-Brown, modified Wiebols-Cook, modified Lade and Drucker-Prager. Among these, the first two criteria ignore the effect of intermediate principal stress and hence are derivable from conventional triaxial test data [7]. On the other hand, the last three criteria consider the influence of the intermediate principal stress and thus are derivable from true triaxial or polyaxial test[7].

The Mohr-Coulomb criterion is the most commonly used rock failure criterion[3]. However, this criterion is found to be too conservative in estimating collapse pressure. It is because Mohr-Coulomb criterion ignores the strengthening effect of intermediate stress.

Hoek-Brown is an empirical criterion that uses the uniaxial compressive strength of the intact rock material as a scaling parameter and introduces two dimensionless strength parameters m and s. These constants depend on the properties of the rock and on the extent to which it had been broken before being tested[7]. One disadvantage of the Hoek-Brown criterion is that correlations are not readily available in the published literature to relate m to commonly measured geophysical well logs[7]. Also relationships are not available to relate m to angle of internal friction.

The Drucker-Prager criterion combines the Mohr-Coulomb and Von Mises criteria. This criterion has three options- inner, middle and outer circles. Among these three options, the outer circle is considered to produce the most realistic result of collapse pressure prediction[8]. Although conservative, the Mohr-Coulomb criterion produces more realistic outcome than Drucker-Prager[4]. Al-Azmi and Zimmerman[3] concluded that Drucker-Prager criterion always underestimates the required mud weight due to the incorrect strengthening effect that arises from the use of the octahedral normal stress instead of the effective mean stress.

Modified Lade criterion uses the same rock parameters as the Mohr-Coulomb criterion (cohesion and internal friction angle). This criterion correctly describes the influence of the intermediate principal stress on rock strength[4]. As a result, this criterion is found to produce more realistic prediction compared to Mohr-Coulomb and Drucker-Prager criteria[4].

3. PBORE-3D

PBORE-3D is a user-friendly software developed by

Poromechanics Institute located in Norman, Oklahoma[8]. It can be used to perform mechanical stability analyses of inclined boreholes drilled in an isotropic or anisotropic porous rock formation. PBORE-3D can evaluate time dependent stress state and pore pressure distribution for a given mud weight. It can also obtain time-dependent critical mudweight windows for the fracturing and collapse failure modes and provide curves varying the mudweight as a function of the effective fracturing stress or effective collapse stress depending on the failure mode selected. The software can also perform mud weight analysis evaluating critical mud weight varying hole angle, azimuth as well as depth. All of the above can be done for elastic, thermoelastic, viscoelastic, chemoelastic, poroelastic, porothermoelstic, poroviscoelastic, porochemoelastic (potential or solute transport), porochemothermoelastic (potential or solute transport), dual-poroelastic, and dual-porochemoelastic (for fractured formations) type of analyses [9].

PBORE-3D provides purely analytical solutions with the facility of using numerous models. Using PBORE-3D, it is possible to perform either permeable or impermeable formation analysis. This means that the software can be used to simulate two types of situations: diffusion of wellbore fluid into the formation and formation of a good mud cake which restricts the communication between the wellbore and the pore fluids. Generally, the impermeable formation analysis is performed to simulate conditions during drilling through an impermeable formation (such as shale with permeability in the nanoDarcy range) or shortly after drilling when no pore pressure penetration occurs.

4. ASSUMPTIONS FOR ANALYSIS

The following assumptions are made-

- Compressive stress is positive
- The longitudinal axis of the horizontal wellbore is aligned with one of the principal in-situ horizontal stress directions
- Constant in-situ field stress
- Permeable formation
- Isotropic rock properties
- The rock is poroelastic
- No bedding plane
- Incompressible drilling and pore fluid
- Isothermal conditions

5. INPUT DATA USED

A large oil field developed using four platforms with a total of 81 well slots is located in the southern part of the Norwegian North Sea in water depths of around 70 m. A core was cut from the Eocene and extensively tested and characterized. Typical field data are showed in Table 1. The data are collected from Nes et al[10].

The mechanical properties showed in Table 1 for Cardium Formation are estimated in order to perform a wellbore stability analysis for a horizontal well drilled in this formation in a field located in West-central Alberta. The rock mechanical properties are estimated from dynamic elastic properties calculated from sonic and bulk density log data using empirical correlations derived for rocks with similar lithologies. The data are collected from McLellan et al[11].

Table 1: Input data used for simulation

Parameter	Eocene shale	Cardium sandstone	Cardium interbedded sandstone/shale
TVD	2051 m	2400 m	2400 m
σ_v	20 KPa/m	24 KPa/m	24 KPa/m
σ_H	18.04 KPa/m	24 KPa/m	24 KPa/m
σ_h	18.04 KPa/m	18.6 KPa/m	18.6 KPa/m
p	15.6 KPa/m	10 KPa/m	10 KPa/m
C_o	3.85 MPa	13 MPa	5 MPa
α_F	1^o	35^o	35^o
E	800 MPa	15000 MPa	4000 MPa
υ	0.40	0.25	0.30
T_o	0 MPa	0 MPa	0 MPa
κ	0.001 mD (assumed)	0.5 mD	0.1 mD
$\theta_Z(\sigma_H)$	0^o (assumed)	45^o	45^o
θ_Z(well)	0^o	135^o	135^o
θ_{well}	90^o	90^o	90^o

6. SIMULATION RESULTS & ANALYSIS

The mechanical borehole stability of a 12 ¼" horizontal borehole drilled in three different formations under three different drilling conditions is simulated and analyzed.

6.1 Eocene Shale

The Eocene shale has isotropic horizontal stresses and the maximum in-situ principal stress is the overburden stress. Fjær et al[2] showed an analysis for similar case scenario. They observed that the stable mud weight range is continuously narrowed down with the increase in borehole inclination angle. For a horizontal well, they found a minimum mud weight close to the fracture pressure. Similar results are also observed for the Eocene shale.

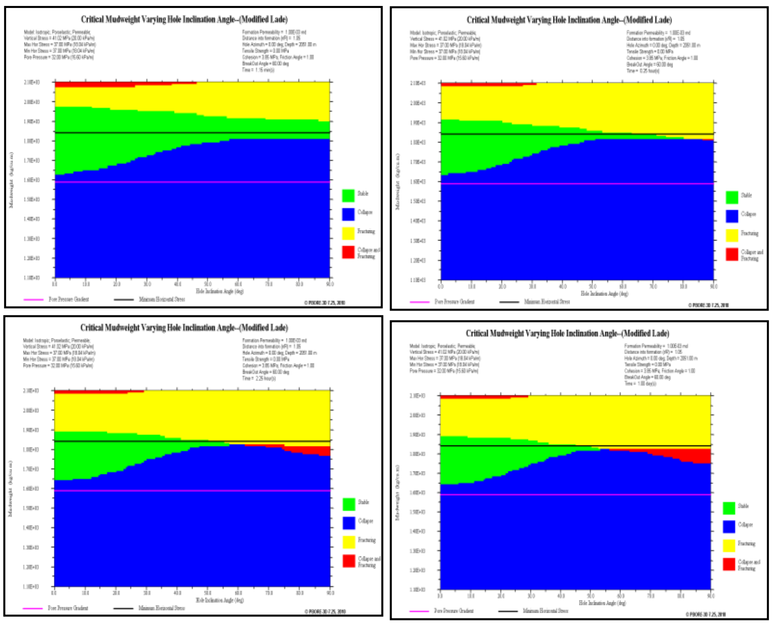

Fig.2: The change in stable mud weight with borehole inclination for different time intervals (60^o breakout angle)

Figure 2 shows the change in safe mud weight window with time for the Eocene shale (five percent into the formation from the borehole wall) for different borehole inclinations. It is observed that there exists a narrow stable mud weight window initially for 60^{o} breakout angle for a horizontal borehole. However, the safe mud weight window disappears after a very short time and for all the mud weights considered, there will be either fracture, collapse or both afterwards.

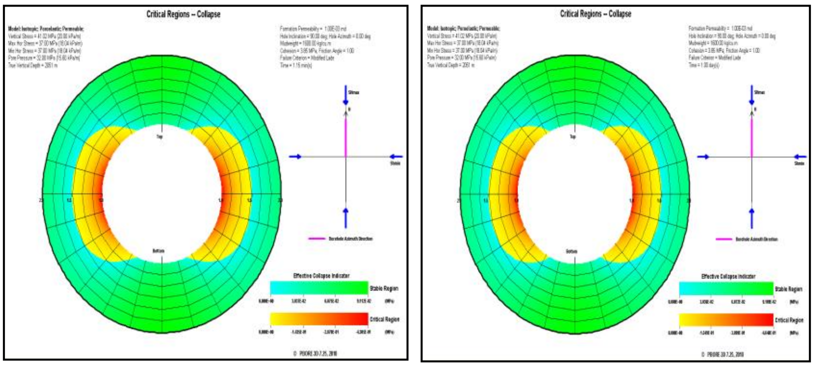

Fig.3: Critical regions for near balanced condition – after 1.15 minutes (left) and 1.0 day (right)

Figure 3 shows the critical collapse regions in the Eocoene shale for a near balanced situation. It can be seen that the critical regions in the shale do not change much with time for near balanced condition. 1600 kg/m^3 results in a static wellbore pressure of 32.2 MPa which is just a little over the pore pressure (32 MPa). If the cavings are efficiently circulated out of the borehole before proceeding further, there will be no more cavings falling into the bore hole afterwards. Simulation also has been performed for a time interval of one month and it is found that the critical collapse regions do not change considerably.

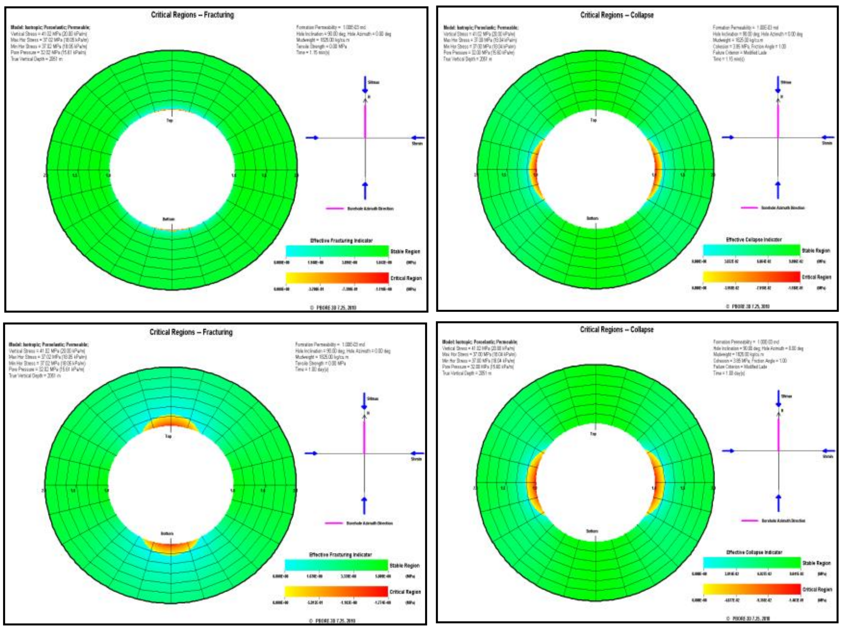

Fig.4: The critical fracturing (left) and collapse (right) regions for overbalanced condition

Figure 4 shows the critical fracturing and collapse regions for a mud weight of 1825 kg/m^3. This mud weight results in a hydrostatic pressure of 36.7 MPa which is approximately 5 MPa over the pore pressure. It can be seen that the collapse region is smaller compared to that of the near balanced condition. However, there exists fracturing region for the current mud weight which is not seen for the previous mud weight. Both fracturing and collapse regions extend with time.

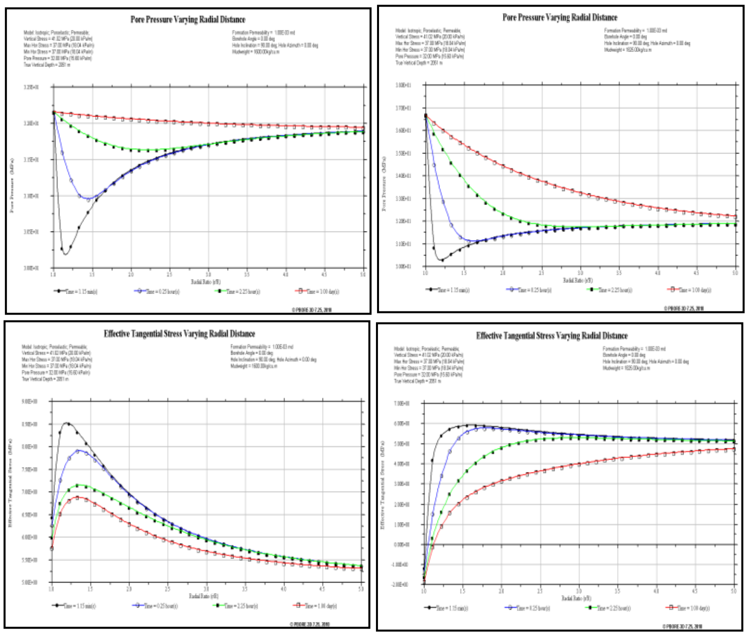

Fig.5: Plot of pore pressure and effective tangential stress against radial distance for near balanced (left) and overbalanced (right) conditions

Figure 5 shows the plots of pore pressure and effective tangential stress for near balanced and overbalanced conditions. As the formation is considered nonlinear (i.e. elastic modulus is dependent on stress state), stress concentration occurs at some distance into the formation than at the borehole wall (where stress concentration would have occurred if the formation were assumed linearly elastic.). The plots also show that after some time, the pore pressure approaches the in-situ pressure in both cases. To be noted that, the effective tangential stress is negative at the borehole wall up to some distance into the formation for 1825 kg/m^3 mud weight. This is because tensile failure or hydraulic fracture occurs at this mud weight. On the other hand, the effective hoop stress is always positive for the near balanced condition. This indicates that there will be no tensile fracture at the near balanced condition.

Figure 6 shows underbalanced condition for the Eocene shale for a mud weight of 1400 kg/m^3. This mud weight gives an underbalance of 4 MPa. The plot shows that there will be spalling initially which will disappear afterwards. The effective radial stress curve further confirms this as the effective radial stress is negative initially for the time interval of 1.15 minutes. But the effective radial stress is positive afterwards for all the time intervals. However, the pore pressure decreases with time due to the diffusion of the pore fluid into the borehole.

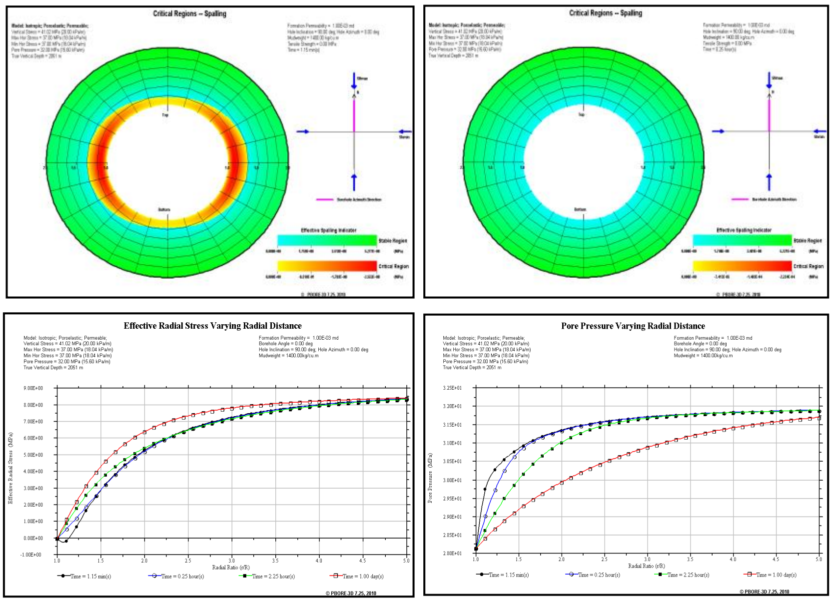

Fig.6: Underbalanced condition (spalling)

From the above analyses for the Eocene shale, it is observed that drilling at near balanced condition will produce collapse region around the borehole initially which will not increase much with time. Also the near balanced condition produces no tensile fracture into the borehole.

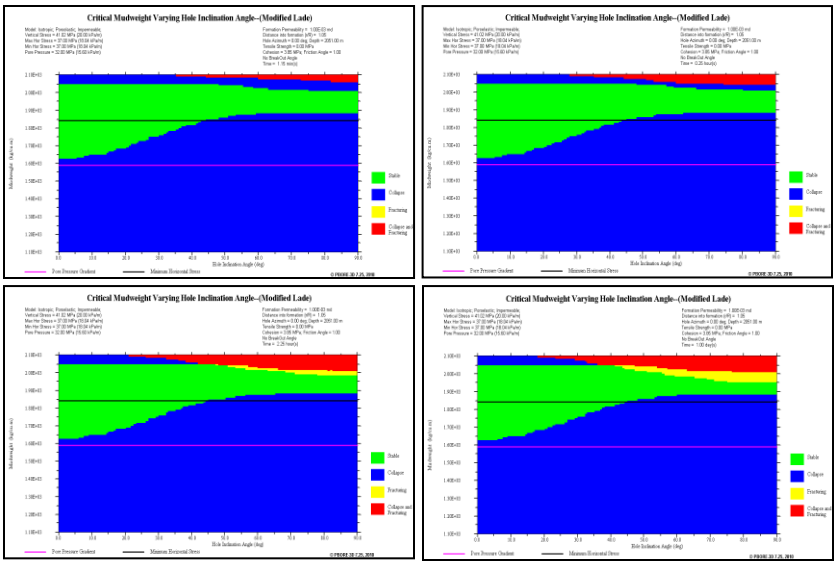

Fig.7: Mud window for different borehole inclinations at different time intervals (0^o breakout angle and impermeable model)

Figure 7 shows the stable mud weight window by using impermeable model. Comparing with Figure 2 (which uses permeable model), it can be apprehended that the use of a mud that produces good filter cake and thus restricts the communication between the borehole fluid and the pore fluid effectively provides a wider stable mud window. Although effective mud cake cannot be established on shale traditionally, use of non-wetting drilling fluid or a fluid which contains molecular species (e.g. polymers) that block the shale surface can be a useful option[2].

It is to be noted that the in-situ horizontal stresses are isotropic. Therefore, mechanical wellbore stability is unaffected by the choice of wellbore azimuth.

6.2 Cardium Sandstone

It is conventional to drill a horizontal borehole in the direction of minimum horizontal principal stress in case of anisotropic horizontal stress field[12]. This is because the difference between the principal stresses perpendicular to the borehole is reduced and results in a minimum stress concentration around the borehole. Fjær et al[2] performed an analysis and showed that horizontal well drilled in the direction of minimum horizontal stress for anisotropic in-situ horizontal stress field, exhibits improved borehole stability. Hence the horizontal well azimuth for the Cardium sandstone is considered to be same as that of the minimum horizontal stress to begin with.

The Cardium sandstone has high cohesion and angle of internal friction. These indicate that the formation has high shear strength. Hence the stable mud window for a horizontal well drilled in Cardium sandstone is considerably wide upto one day after drilling as showed in Figure 8. However, the stable mud window narrows down considerably for time intervals beyond five days. The plot (right) in the bottom row of Figure 8 shows that the stable mud window not only narrows down, but also reduces in magnitude considerably after 10 days.

Figure 9 shows a sensitivity analysis for time dependent borehole collapse for two different borehole azimuths – one in the direction of minimum horizontal stress and the other in the direction of maximum horizontal stress. It is observed that a horizontal borehole drilled in the direction of minimum horizontal stress is more stable compared to that drilled in the maximum horizontal stress direction for near balanced drilling conditions. This is in agreement with Fjær et al[2].

For well azimuth in the direction of minimum horizontal stress, the borehole is always stable for the balanced drilling condition. But for the well azimuth parallel to maximum horizontal stress, the collapse region appears immediately after drillout and it continues to increase with time leading to an unstable borehole condition.

For the Cardium sandstone, a stable horizontal borehole can be drilled at balanced drilling condition provided that the wellbore azimuth is parallel to the minimum horizontal stress. Further analysis showed that underbalanced drilling is also a viable option for this formation as it is quite strong. Underbalanced drilling is advantageous as it provides higher ROP and avoids formation damage caused by the invasion of drilling fluid into the formation due to overbalance.

6.3 Cardium Interbedded Sandstone/Shale

The stable mud window for a horizontal hole drilled in the direction of minimum horizontal direction in Cardium interbedded sandstone/shale is found not to change appreciably for a time interval varied between 1.15 minutes and 1 day. Like the Eocene shale, it is observed from simulation that more cavings will be produced when the pressure in the wellbore decreases

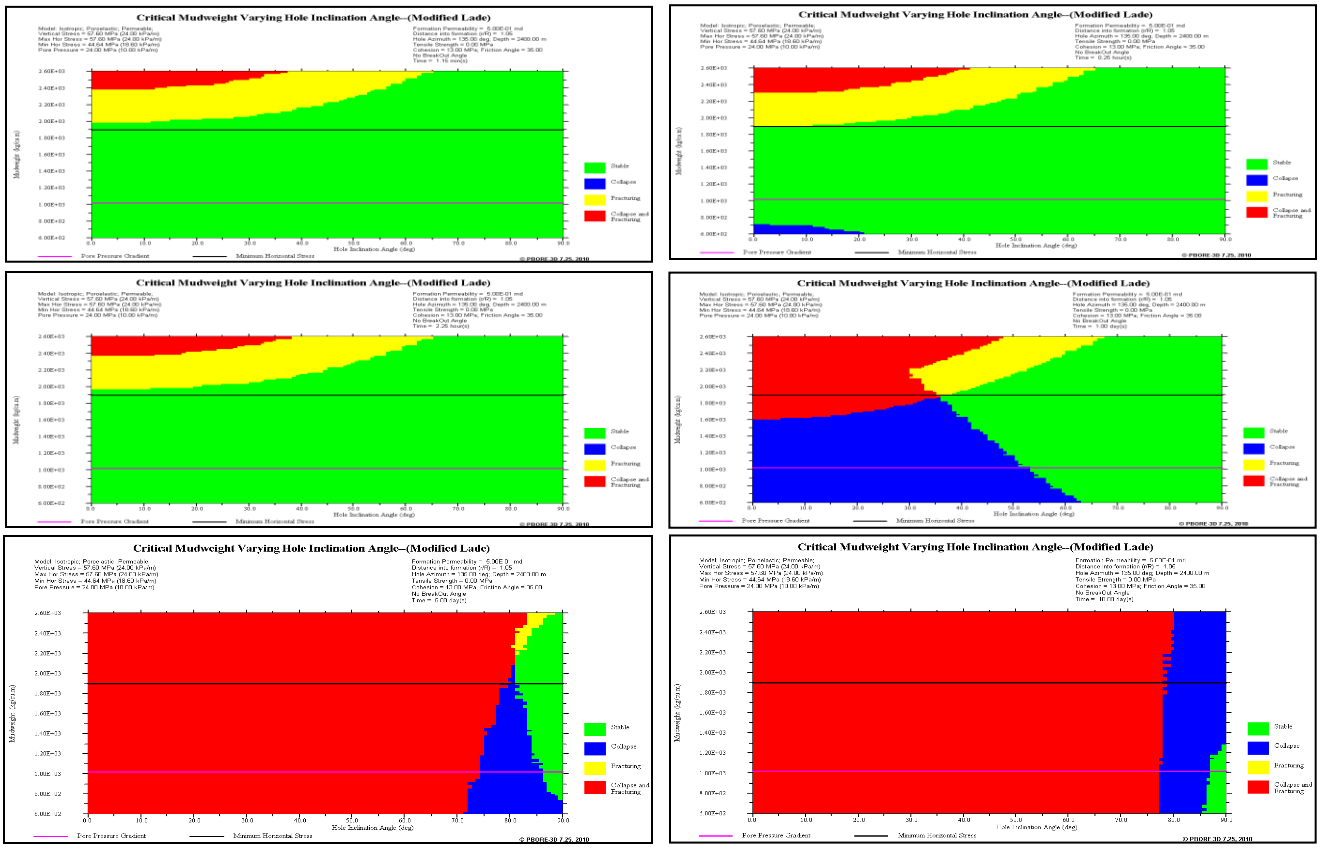

Fig.8: Change in stable mud window with borehole inclination for different time intervals (no breakout angle) for Cardium sandstone

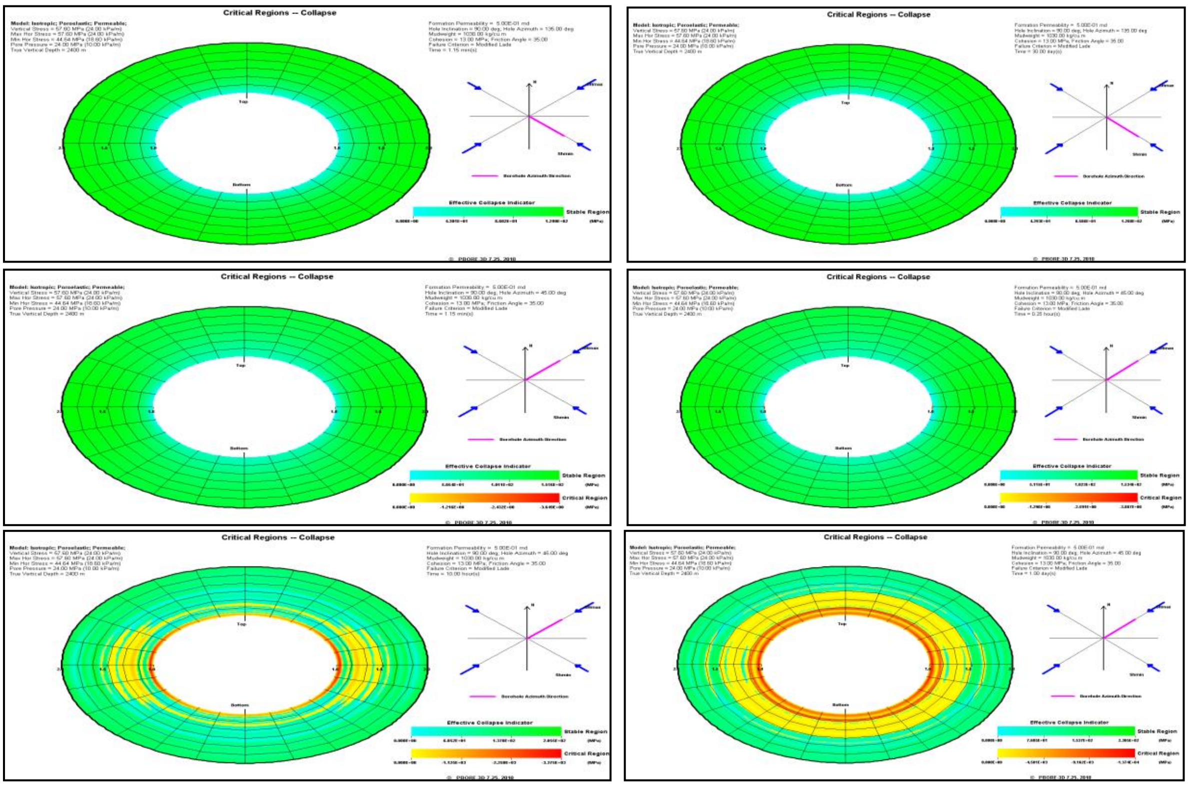

Fig.9: Critical collapse region for well azimuth parallel to minimum horizontal stress (first row) and parallel to maximum horizontal stress (second and third row) at different time intervals

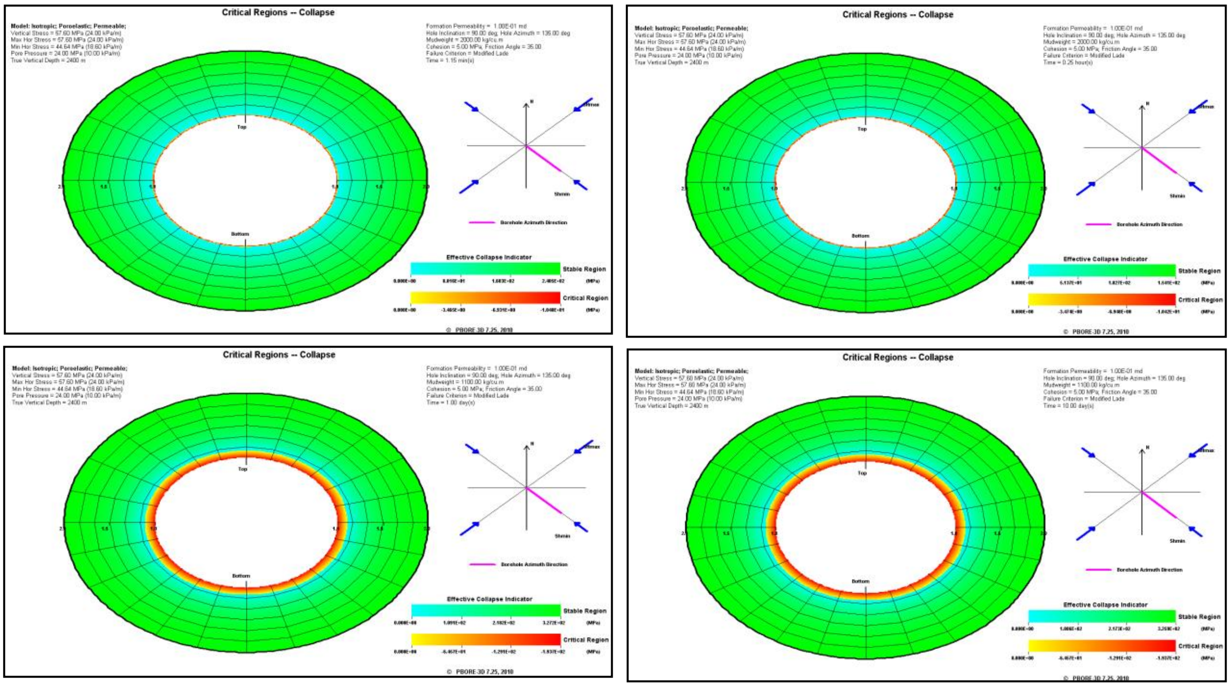

Fig.10: Critical collapse regions for 2000 kg/m^3 (top row) and 1100 kg/m^3 (bottom row)

due to diffusion of the borehole fluid into the formation (Figure 10). Depending on the formation permeability, the time for pressure equilibration will vary. In the figure, the pressure equilibration is considered to be attained after one day and the equilibrating pressure is assumed to correspond to a mud weight of 1100 kg/m^3. It can be observed from the simulation that the amount of cavings will not change much for the present case after one day at the mud weight of 1100 kg/m^3.

7. Conclusion

In the present work, simulation results obtained for time-dependent mechanical borehole stability analysis presented using a poromechanics simulator PBORE-3D. The poroelasticity theory is used along with consolidation effect to simulate borehole conditions with time under varying drilling conditions for a virtual 12-1/4¨ horizontal borehole drilled in Eocene shale, Cardium sandstone and Cardium interbedded sandstone/shale.

Based on the analysis presented in the previous section, it is realized that stable mud window depends on time as the stress state of the formation surrounding a borehole changes with time. Use of an overbalanced mud weight reduces the amount of cavings generated during drilling. It is worth noting that drilling in near balanced condition improves time dependent borehole stability for the three cases presented earlier. Amount of cavings generated initially is much higher in near balanced condition compared to overbalanced drilling. However, the collapse region is not seen to change much with time which indicates that less or no more caving will be generated afterwards under near balanced drilling condition.

Only one of the four sources of time dependent borehole failure is considered in the present work. Simulation work to be performed incorporating the other three sources of time dependent borehole failure is recommended for getting a more realistic scenario of borehole stability using PBORE-3D.

8. ACKOWLEDGEMENT

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10. NOMENCLATURE

Symbol	Meaning	SI Unit
σ_1	Major in-situ principal stress	(Pa)
σ_2	Intermediate in-situ principal stress	(Pa)
σ_3	Minor in-situ principal stress	(Pa)
TVD	True Vertical Depth	(m)
σ_v	Vertical stress	(Pa)
σ_H	Major horizontal stress	(Pa)
σ_h	Minor horizontal stress	(Pa)
P	Pore pressure	(Pa)
C_o	Cohesion	(Pa)
α_F	Friction angle	(^{o})
E	Young's modulus	(Pa)
υ	Poisson's ratio	-
T_o	Tensile strength	(Pa)
κ	Permeability	(Darcy)
$\theta_Z(\sigma_H)$	Azimuth of σ_H	(^{o})
θ_Z(well)	Well azimuth	(^{o})
θ_{well}	Well Inclination	(^{o})