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MECHANICAL BOREHOLE STABILITY ANALYSIS USING PHASE2

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ABSTRACT

Borehole instability is an operational problem and typically accounts for 10% of the drilling costs. The change in the stress state caused by drillout can lead to mechanical borehole instability if the wellbore pressure is below the minimum required borehole pressure (shear failure) or above the fracture pressure (tensile failure). A FEM tool, Phase2, is used in the current work for mechanical borehole stability analysis of a virtual vertical borehole drilled in sandstone for three different hydrostatic wellbore pressures (15, 34 and 50 MPa) for the geomechanical and rock parameter values collected from the North Sea field P2-NE. An in-situ constant pore pressure of 30 MPa is considered (at 2743 m TVD). The surrounding rock is simulated as an isotropic elastic (before yielding) and perfectly plastic material (during yielding).

The borehole is found stable for the overbalanced condition. However, when the wellbore pressure is reduced to half of the pore pressure, borehole collapse is observed. On the other hand, fractures appear in the formation when the wellbore pressure is raised to the formation breakdown pressure.

Phase2 used typically in geotechnical engineering, is used for the first time (to the best of our knowledge) for borehole stability analysis in the petroleum engineering field and the simulation results obtained are in agreement with the theoretical findings published in the literature for the borehole conditions considered.

Keywords: Phase2, Mechanical Borehole Stability, Isotropy, Perfectly Plastic Material.

1. INTRODUCTION

The two main causes of non-productive time (NPT) are hole problems (addressed by hydraulics measurement and wellbore-integrity measurement), and drillstring and tool failure (addressed by drillstring-integrity measurement) [1]. Ensuring formation integrity (i.e. ability of the formation to withstand applied load without failure) is considered to be a major challenge to the oil industry in order to ensure efficient and cost effective drilling.

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].

Borehole instability problems during drilling may arise solely due to inadequate or too high mud weight (mechanical problem) [4]. Drilling a stable borehole requires proper choice of adequate mud weight. It is seen that too low mud weight results in collapse and fill problems, while too high mud weight results in mud losses or stuck pipe. However, practice has also shown that excessive variations in mud weight lead to premature borehole failure due to formation fatigue [5].

Subsurface formations are exposed to compressive stresses and pore pressure. A balanced stress condition exists before a well is drilled into the formation. When a well is drilled, the drilling fluid replaces the stressed rock material. Unlike the original rock mass, the drilling fluid can only support the normal stresses on the well wall partially but no shear stresses along the wellbore wall [6]. This mismatch between the drilling fluid and the removed rock mass in supporting the surrounding formation leads to an altered stress state around the well. The redistributed stresses can lead to borehole failure when the formation strength is exceeded.

There are two types of mechanical borehole failure – compressive and tensile [2]. Compressive failure occurs when the wellbore pressure is too low compared with the rock strength and the induced stresses. On the other hand, tensile failure occurs when the wellbore pressure is too high. However, tensile failure may also occur when the well pressure is lower than the pore pressure [7]. A further detail on mechanical wellbore instability can be found in [8].

Calculation and analysis of the redistributed stress state is the key to predict borehole stability. Table 1 (modified after Tare et al [4]) shows the field and operational parameters that influence borehole stability analysis. Only the parameters shown in italic are taken

Table 1: Field and operational parameters influencing borehole instability (Modified after Tare et al)

Drilling Fluid	Drilling Operations	Rock Properties	Drill String	In-situ Stresses
Composition (WBM, OBM)	Hole orientation (Azimuth)	Strength (UCS)	BHA	Overburden & Horizontal Stresses
Pressure (ESD, ECD)	Open Hole Time	Permeability & Porosity	Vibrations	Pore Pressure
Flow Rate & Rheology (Density, Viscosity)	Tripping (Surge & Swab)	Mud-Rock Interaction (Physico-chemical)	Rotation	
Temperature	Drilling Methods (OBD, MPD & UBD)			

into account in the present work. The rock surrounding the borehole is simulated as an isotropic, porous and perfectly plastic material during yielding.

In this paper, the results of mechanical borehole stability analysis obtained by using a finite element tool, Phase2, are presented. With the help of a virtual 8 ½´´vertical wellbore drilled in sandstone, three wellbore pressure conditions are simulated and the results are presented. Also the operational procedure used in the model development is outlined.

To the best of our knowledge, this is the first time when Phase2 is used for borehole stability analysis in the petroleum engineering field. Typically used for geotechnical analysis, Phase2 is used in the current work as it can generate meshes faster and thus makes the numerical model development easier and less time consuming. The geomechanical data used in the analysis are collected from the offshore Norwegian field P2-NE published by Colins [9].

2. PHASE2, A FEM TOOL

Phase2 is a two dimensional elasto-plastic finite element program created by Rocscience Inc. It can be used for calculating stresses and displacements around underground openings. It is used to solve a wide range of mining, geotechnical and civil engineering problems.

Phase2 consists of 3 modules- MODEL, COMPUTE and INTERPRET. Each of these modules can run as standalone programs. They can interact with each other as illustrated in Figure 1.

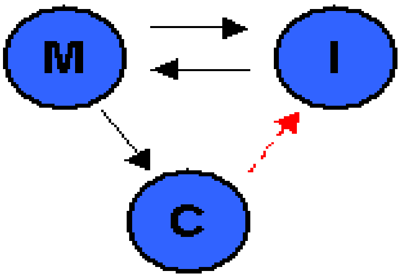

Fig 1. The interaction between the three program modules of Phase2- MODEL (M), COMPUTE (C) and INTERPRET (I) [10]

In Phase2, MODEL is the pre-processing module. It is used for entering and editing the model boundaries, support, in-situ stresses, boundary conditions, material properties and creating the finite element mesh.

COMPUTE carries out the finite element stress analysis for a Phase2 model. It uses Gaussian elimination, conjugate gradient or pre-conditioned conjugate gradient iteration to solve the matrix representing the system of equations defined by the model.

INTERPRET is the post-processing module in Phase2. It is used for data visualization and interpretation of the Phase2 analysis results. INTERPRET can display data contours (e.g. displacement, stress, strength factor). It can also be used to present graphical display of results for material queries. However, COMPUTE must be run on a file before results can be analyzed with INTERPRET.

Phase2 uses a compressed file format to store all input and output files for a given model. The compressed (zip) file has .fez extension.

Phase2 uses an advanced meshing algorithm which enormously simplifies the task of mesh generation for the user. It has the ability to generate a regular mesh of triangles and quadrilaterals with a single mouse click.

Phase2 can create and analyze two general types of models:

Plane Strain: A plane strain model assumes that the excavations are of infinite length in the out-of-plane direction and hence the strain in the out-of-plane direction is zero.

Axisymmetric: An axisymmetric analysis is used to analyze a three dimensional model which is rotationally symmetric about an axis. For an axisymmetric model, the input is two dimensional but the analysis results apply to the three dimensional problem.

Phase2 considers two possible failure modes of a solid element: tensile or shear. Either or both of these modes may occur in a given element.

3. INPUT DATA

The data for the work are collected from a publication of Colins [9] where geomechanical feature of P2-NE is discussed. P2-NE is a Norwegian field located in the north-east corner of Block P2a in the North Sea. The field contains sandstones. The in situ stress and rock parameters shown in Table 2 are found at a vertical depth of 2743m.

Based on borehole breakout analysis, the maximum horizontal stress orientation is found 130°-310°. Specific weight of pore fluid is assumed 10.791 KN/m^3. The formation breakdown gradient is 0.81 psi/ft (= 0.018 MPa/m).

The diameter of the vertical borehole is 8 ½´´ (= 0.22 m). The analysis is intended to be done for three different wellbore pressures: 15, 34 and 50 MPa. For the analysis, the Mohr-Coulomb failure criterion will be used assuming zero dilation angle (non-associated flow).

Table 2: In situ and rock strength parameters

Category	Parameter	Value
In situ stress	σ_v	62 MPa
	σ_H	46.5 MPa
	σ_h	38 MPa
	p_f	30 MPa
Rock strength	T_o	0
	α_F	38.7°
	υ	0.16
	C_o	8.6 MPa
	E	20 GPa

4. ASSUMPTIONS

The following assumptions are made for the analysis:

- Compressive stress is positive
- The longitudinal axis of the wellbore is aligned with the vertical stress direction
- Constant field stress (since the wellbore section is located deep into the subsurface)
- Plane strain condition (since the dimension in the axial direction is much larger compared to those in the horizontal directions)
- Rock properties are isotropic
- Rock is linearly elastic (before yielding) and perfectly plastic (after yielding)
- The external boundary is fixed or pinned
- 100% effective mudcake (i.e. the borehole wall is impermeable)
- Isothermal condition
- Constant wellbore pressure

5. NUMERICAL MODEL

A 40 segment circle of radius 0.11 m is created in Phase2 to mimic the borehole. The surrounding formation is modeled by a box type external boundary with an expansion factor five. Three noded triangular elements are used in the model. The graded mesh has a gradation factor 0.1. The external boundary is considered as fixed. The wellbore pressure is considered uniformly distributed around the wellbore. The internal well pressure acts normal to the wellbore wall. The pore pressure (30 MPa) is inserted into the model using Grid (Pore Pressure) method and Modified Chugh grid interpolation technique. The model is shown in Figure 2.

The following construction sequence is used in creating the Phase2 model:

- Project Settings: All the default settings are used except the Groundwater. Under the Groundwater tab, the Grid (Pore Pressure) is chosen as the method and Modified Chugh is set as the grid interpolation technique. The pore fluid unit weight is set to 0.010791 MN/m3.
- Boundaries: Using the Add Excavation option, a circle is drawn. The circle radius is 0.11 m and it has 40 segments. Using the Add External option, a box type external boundary is created which has an expansion factor 5.
- Mesh: Using the Mesh option from the main menu, a graded mesh of three noded triangular elements is generated.
- Properties: This option is used to define material properties. The elastic type is set to Isotropic and the material type is set to Plastic. The Failure Criterion is set to Mohr-Coulomb. All the rock parameters are inserted. Using the Assign Properties option, the borehole is excavated.
- Groundwater: Using this option, the pore pressure grid is inserted. In this case, the Water Pressure Grid is chosen from the Groundwater dropdown list.
- Loading: Field Stress Properties under the Loading option is used to define constant in-situ field

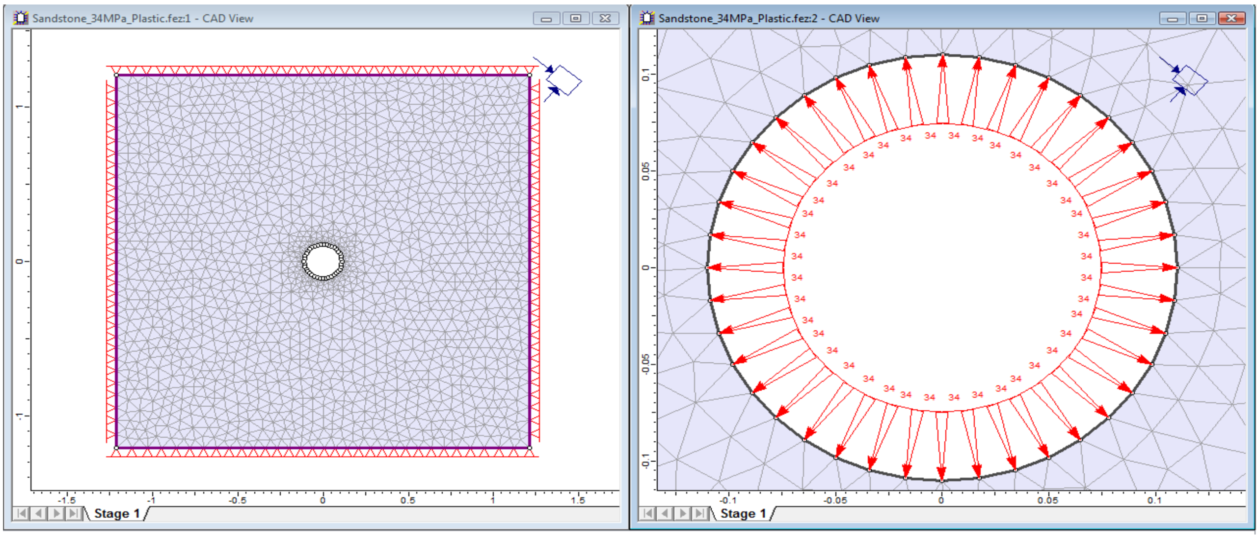

Fig 2. The Phase2 model- before applying wellbore pressure (left) and the wellbore after applying 34 MPa (right)

stresses and their orientation. Add Uniform Load under Distributed Loads submenu is used to apply wellbore pressure.

- Compute: After saving the model thus created, the Compute button is used to run the simulation.
- Interpret: The analysis module of Phase2, Interpret, is used to analyze the results obtained after simulation.

6. ANALYSIS RESULTS

The simulation is run for three different wellbore pressures- 15, 34 and 50 MPa. Here the analysis results for 34 MPa are presented first. Then the results for 15 and 50 MPa are presented.

34 MPa

The well pressure is higher than the pore pressure (30 MPa). This represents the usual overbalanced drilling situation. The contour plots for in-plane major and minor principal stresses (σ_1, σ_3), i.e. the hoop stress and the radial stress, are shown in Figure 3. The plots show that stresses in the direction of minor in-situ horizontal stress (σ_h) are higher compared to that in the direction of major in-situ horizontal stress (σ_H).

Figure 4 shows the plot of the strength factor around the borehole wall when the well pressure is 34 MPa. The strength factor is more than 2 at all points of the borehole wall indicating that the borehole will not fail if drilled with this pressure. Consequently there is no yielded element found when the *Display Yielded Elements* button in INTERPRET is switched on.

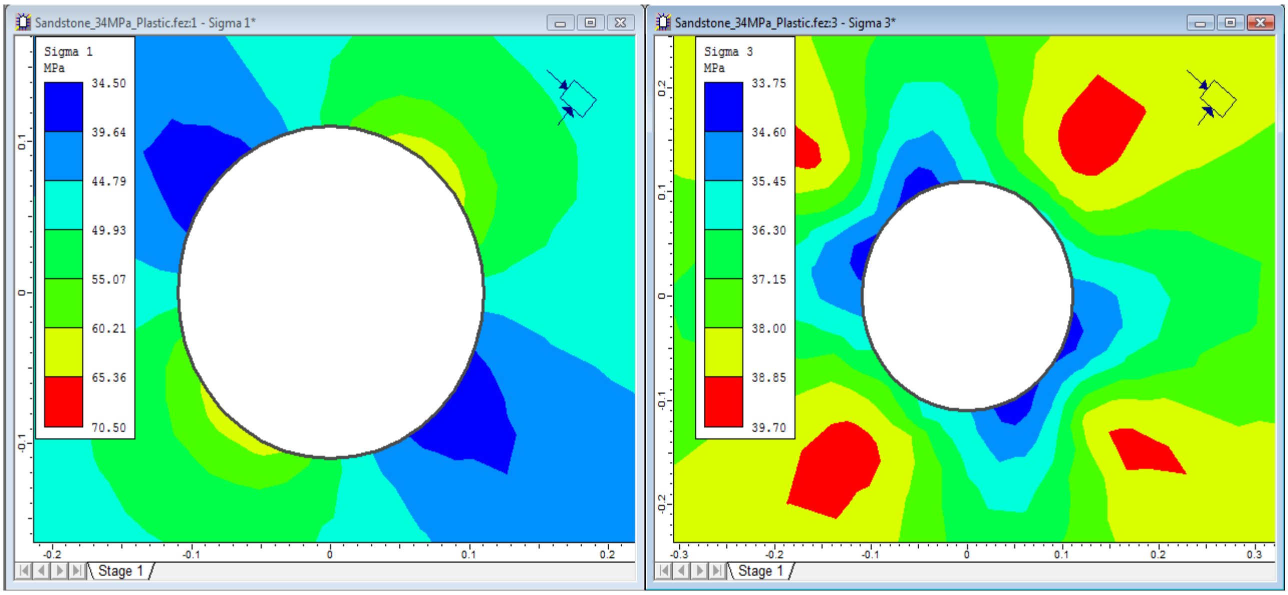

Fig 3. Contour plots of major in-plane horizontal stress (left) and minor in-plane horizontal stress (right) for a well pressure of 34 MPa

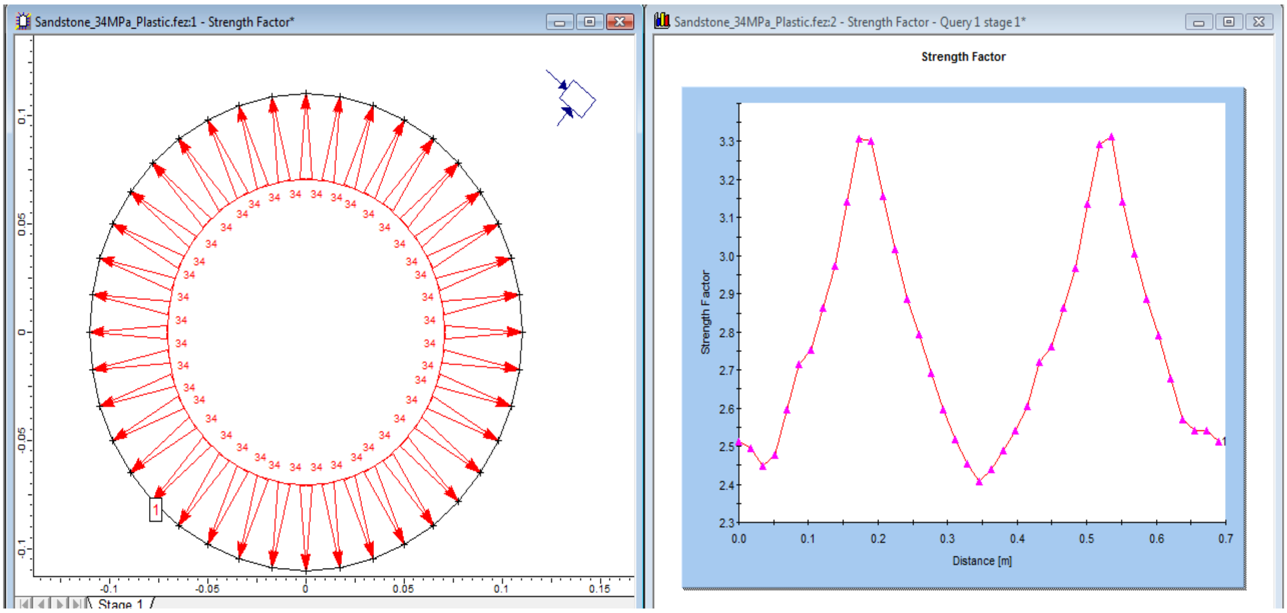

Fig 4. Plot of strength factor around the borehole for a well pressure of 34 MPa

Figure 5 shows pore pressure distribution in the vicinity of the borehole. It is observed that the pore pressure is zero at the wall and it gradually increases to 30 MPa over a small region of 20 mm. Beyond this region of 20 mm, the pore pressure remains constant at 30 MPa for all other points in the model. This happened as the borehole is assumed to be impermeable due to the formation of mudcake.

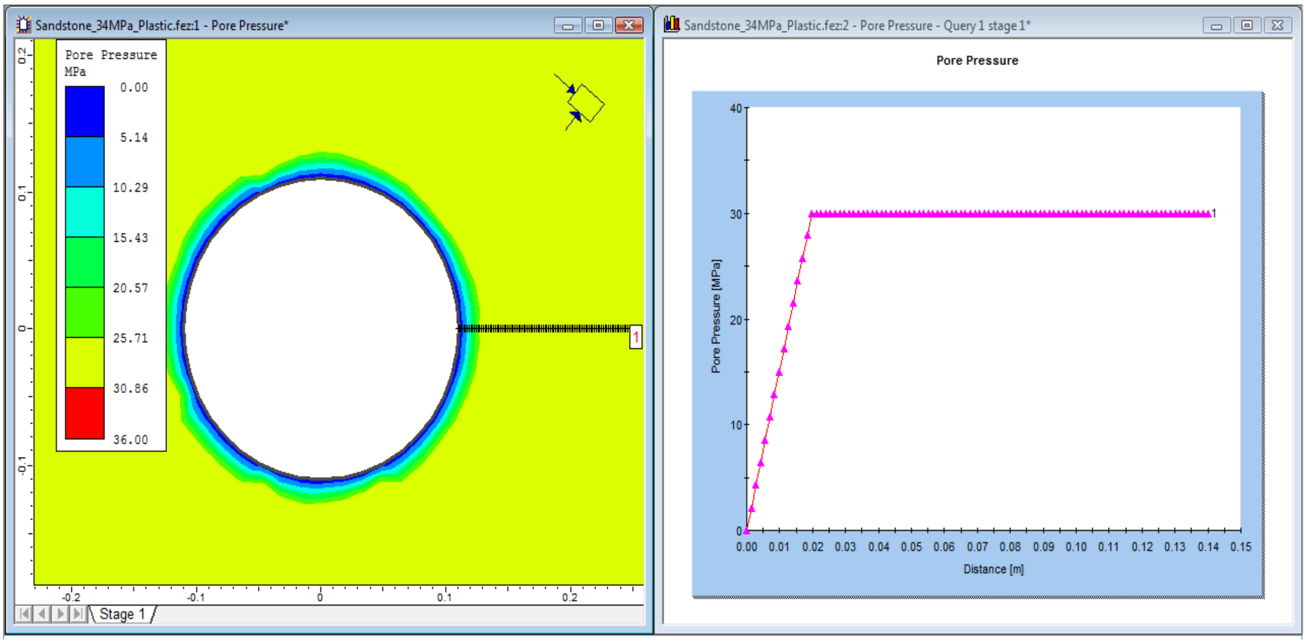

Fig 5. Pore pressure distribution near the borehole for 34 MPa

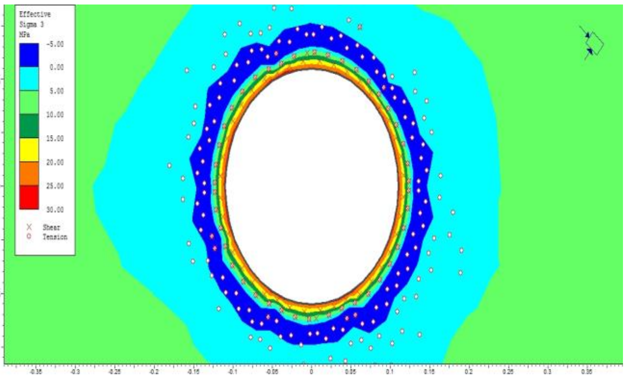

Fig 6. Contour plot of effective minimum in-plane horizontal stress (σ_3') along with the yielded elements for a well pressure of 15 MPa

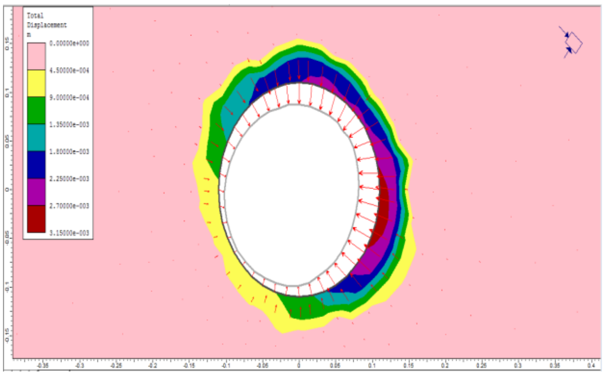

Fig 7. Contour plot of total displacement along with the deformation vector and the deformed borehole boundary for a well pressure of 15 MPa

In this case, the well pressure is less than the pore pressure. As a result, the effective minor in-plane principal stress (σ_3'), i.e. radial stress, becomes negative. This causes tensile failure and formation of sharp, blade-shaped fragments of the rock spalling off into the borehole.

Figure 6 shows the contour plot of σ_3' around the borehole. It is seen that σ_3' becomes negative close to the borehole. This leads to tensile failure. The plot shows 227 yielded elements out of which approximately 50% have yielded due to tension. Close observation also reveals that elements at the borehole wall endure shear failure. This is plausible as the wellbore pressure is less than the minimum required pressure to prevent borehole collapse. It is to be noted that with reduced borehole pressure, the hoop stress increases. So increasing hoop stress along with a well pressure lower than the collapse pressure leads to shear failure at the borehole wall.

Figure 7 shows the contour plot of total displacement. The maximum total displacement is found 2.9 mm. The deformed borehole shape and the deformation vectors are also shown. They bear evidence for borehole collapse for the current well pressure of 15 MPa. The scaling factor used in the plot is 10.

This wellbore pressure is close to the formation breakdown pressure at the given depth. When this pressure is applied, tensile failure will occur and fractures will appear in the direction of major in-situ horizontal stress (σ_H) as the hoop stress becomes minimum in this direction. Figure 8 confirms this.

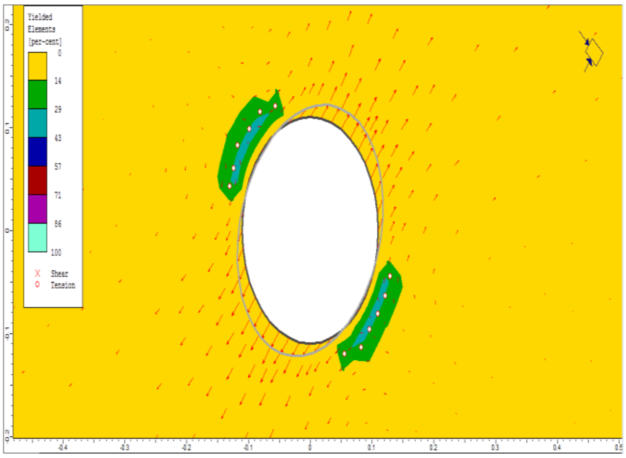

Fig 8. Plot of percent yielded elements and deformation vector along with deformed wellbore boundary when the well pressure is 50 MPa

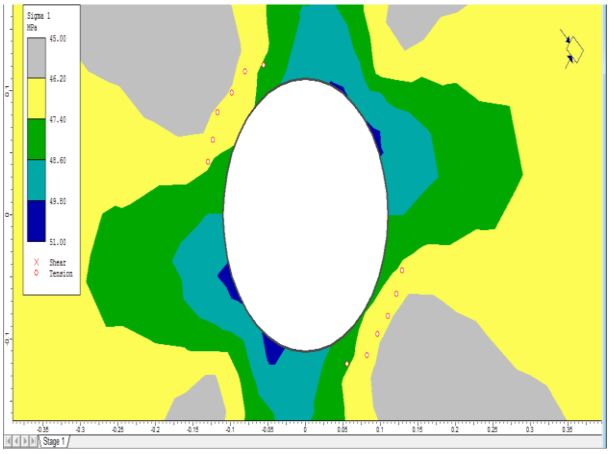

Fig 9. Contour plot of maximum in-plane horizontal stress (σ_1) for a well pressure of 50 MPa

Figure 8 shows the yielded elements (12 in total). They appear in the direction where hoop stress assumes lower values. This is further confirmed by Figure 9 where the contour plot of hoop stress is shown along with the yielded elements. Higher values of hoop stress occur in the direction of minimum in-situ horizontal principal stress (σ_h). The deformed contour is shown using a scale factor of 200 in Figure 8. The maximum total displacement is found 0.106 mm.

Both in Figure 8 and 9, the yielded elements are indicated by circles. This means that the elements fail due to tension only (in accordance with Phase2 setup). This, in turn, confirms the initiation of tensile fractures in the formation at a wellbore pressure close to formation breakdown pressure.

To be noted that the maximum total displacement is very small in this case compared to the case of 15 MPa. The reason behind this is that the borehole does not collapse when the wellbore pressure is 50 MPa. In this case, fractures appear in the formation. These fractures are induced in the formation as the tensile strength of the formation is exceeded. But in the case when wellbore pressure is 15 MPa, the borehole collapses and both shear failure (at the borehole wall) and tensile failure (in the formation surrounding the borehole) occurs. As a result, higher value of total displacement occurs.

7. CONCLUSION

This paper demonstrates the use of Phase2, a finite element program widely used in the field of geotechnical engineering, to simulate borehole conditions under three different borehole pressure situations modeling the surrounding rock as isotropic linearly poroelastic before yielding and perfectly plastic during yielding. A virtual vertical borehole section of 8 ½′′ diameter drilled through sandstone is used for this purpose. The data used in the current work are collected from the North Sea field P2-NE.

A stable borehole is found when the wellbore pressure is higher than the pore pressure by 4 MPa. No yielded element is found for this wellbore pressure. The strength factors around the borehole are also found higher than 2.

When the wellbore pressure is set much lower than the pore pressure, the borehole collapses. Elements yielded by tension and shear are observed. A much higher maximum total displacement is observed for this case compared to the other two cases.

The third case uses a wellbore pressure close to the formation breakdown pressure. In this case, a low value of maximum total displacement is found compared to the case involving borehole collapse. Also yielded elements are found that fail only due to tension.

The paper demonstrates the use of Phase2 for mechanical borehole stability analysis assuming linear poroelasticity before yielding and perfect plasticity after yielding. The results obtained are in agreement with the theoretical findings.

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10. NOMENCLATURE

Symbol	Meaning	SI Unit
σ_v	Vertical Stress	(Pa)
σ_H	Maximum Horizontal Stress	(Pa)
σ_h	Minimum Horizontal Stress	(Pa)
p_f	Formation Fluid Pressure	(Pa)
T_o	Tensile Strength	(Pa)
α_F	Friction Angle	^{o}
υ	Poisson's Ratio	-
C_o	Cohesion	(Pa)
E	Young's Modulus	(Pa)

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