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Deformation modeling around a wellbore using finite element technique

*Rima Chatterjee, Dip Kumar Singha and P. Sangvai**

Summary

In this paper modeling of in-situ stress and deformation around a wellbore is presented using 2D and 3D finite element technique. The present model uses the concepts of poroelasticity theory to compute the stationary 2D and 3D, brittle response of the formation around a borehole that is subjected to compressive horizontal stresses. The 2D and 3D models are analysed to investigate the effects of differential far-field stresses and the effect of drilling mud pressure around the wellbore. Differential stresses are the main cause of the elongation of wellbore parallel to the minimum horizontal compressive stress direction. The direction and relative extension of the observed breakouts at a particular depth are modeled successfully using formation realistic parameters and dimensions, although the exact shape of the wellbore (at all angles) was unknown.

Keywords: *Stress, Wellbore, Finite Element Analysis*

Introduction

The problem of wellbore stability has gained significant importance in the last 10 years as a response to the increasing of exploration of complex areas which represent major engineering challenges in drilling and production (Charlez and Onaisi, 2001). Severe hole enlargement has a long list of consequences, from reducing the drill bit life to causing cleaning hole problems, stuck pipe, poor cementing, logging problems, and often the need to sidetrack (Last, 2001). Rock in natural state is stressed in three principal directions: vertical stress (Sv) and two horizontal stresses. The two horizontal stresses are generally not equal - the maximum and minimum horizontal stresses are expressed as S_H and S_h respectively. As a wellbore is drilled, drilling mud pressure replaces the support lost by removal of original column of rock. Drilling mud pressure being uniform in all directions can not exactly balance the earth stress. Consequently rock surrounding the wellbore is deformed and strained and may fail if the redistributed stresses exceed rock strength (Addis et al., 1993). There are two failure mechanism : tensile failure when drilling mud pressure is very high and rock stress exceeds tensile strength, compressive failure can occur at low or high mud pressure depending on mechanical properties of rock where rock stress exceeds compressive strength. Under compressive failure rocks caves in on spalls off, creating breakouts. The compressive hoop stress around a hole can be large enough to exceed the strength of the rock. When this happens, the rock around a portion of the wellbore fails and stress-induced wellbore breakouts form (Barton et al., 1988 and Zoback et al., 1985).

The objectives of this paper are (a) to build a 2D finite element model (FEM) for a wellbore at a depth of 2800m surrounded by homogeneous rocks under equal and differential far-field horizontal stresses, (b) to build 3D FEM for the same wellbore of 20 m length under differential stress, (c) to investigate deformation and elongation of wellbore under these conditions.

Numerical Models

Finite element technique has been used to compute the deformation and stress trajectories surrounding a circular wellbore drilled into a homogeneous rock mass. Finite element models are generated and stresses are calculated using ANSYS, finite element package. The 2D and 3D area is divided into a number of finite elements connected by nodal points. Each element is assigned a displacement function that is determined by the element's shape and

Department of Applied Geophysics, Indian School of Mines, Dhanbad
**Reliance Industries Ltd., Mumbai*
rima_c_99@yahoo.com

the positions of the nodal points. The displacement function and a stress-strain relationship for the element material fix both the strain and stress distribution in the element as functions of the element nodal point displacement. These functions are handled as a matrix equation for the element. The matrix equation for the whole system of finite elements is solved for the equilibrium nodal point displacements by minimizing the total potential energy of the system with respect to the nodal point displacements.

Well log data such as: density log is generally used to estimate vertical stress of any area. In a normal faulting stress regime vertical stress is greater than the S_H and S_h ($Sv \geq S_H > S_h$). In this paper, horizontal section of a circular wellbore is assumed at a depth of 2800 m. The Sv is calculated at 2800 m depth using vertical stress gradient of 22 MPa/km. Pore pressure is estimated from hydrostatic pressure gradient assuming 0.433 psi/ft (equivalent to 9.33 MPa/km) and it becomes 26.12 MPa at the depth of 2800m. Boundary constraints for these FEMs represent a key element in understanding the modeling results. These include a far-field stresses ($S_H = S_V$ = 62MPa and $S_h = 0.7S_V$ = 44MPa) at the model boundary (Figure 1). Drilling mud pressure of 28MPa is applied at the well boundary. Displacements along x axis and y axis of the model boundaries have been assumed zero values. The 2D model is carried out in the horizontal plane. The ANSYS software represents the von mises stress as equivalent stress magnitude. The von mises stress (Boresi and Schimdt, 2003) for stress models can be expressed in the following form:

von mises stress = $(1/2)^{1/2}[(Sx - Sy)^2 + (Sy - Sz)^2 + (Sz - Sx)^2 + 6\,(\tau xy + \tau yz + \tau zx)^2\,]^{1/2}$

where Sx, Sy and Sz are the normal stresses along x, y and z axes respectively. τxy, τyz τzx are the shear stresses.

To investigate the deformation of homogeneous rock mass of 2x2 sq.m area around a wellbore of diameter 0.5m, mechanical properties of rock mass such as: Young's modulus of 30GPa, Poisson's ratio of 0.27 and density of 2.55gm/c.c have been assumed for modeling. The two numbers of 2D model subjected to equal and differential horizontal stresses (Figures 1 and 2) and one 3D model subjected to differential stress for 20 m long wellbore (Figure 3) are presented with the modeling results.

Results

The resultant displacement for 2D model under equal compressive horizontal stresses shows uniform variation along the wellbore boundary. Wellbore diameter is reduced at all sides (Figure 4). Von mises stress contours show uniform variation of stress ranging 24 to 35 MPa prevailing surrounding the wellbore (Figure 5). The stress vector plot (Figure 6) also show the redistribution of horizontal stress direction around the wellbore.

The next 2D model subjected to differential compressive stresses show deformation of the wellbore wall (Figure 7). Wellbore becomes elliptical with its long axis oriented towards far-field S_h direction. Well diameter is increased along the application of S_h direction and shortened along S_H direction. Figure 8 displays the von mises stress contour, showing the stress magnitude of 54 to 80 MPa and along the direction of long axis of ellipitical wellbore and 32 to 52 MPa along the short axis of the wellbore. The stress vector plot (Figure 9) indicates that the minimum horizontal stress vector is rotated towards the long axis of ellipse aligning parallel to the far-field S_h direction. The maximum horizontal stress vector is aligned perpendicular to the Sh direction. The spalling off the wall due to differential stresses is termed as breakout. Therefore the model results can be verified with any image log of any area under the wellbore condition will indicate the S_h orientation.

The 3D model is generated to observe the variation of deformation and stress vector for a cylindrical wellbore of 20 m length having same diameter. Figure 10 indicates the wellbore deformation, spalling has occurred throughout the wall, the diameter of wellbore is increased along the application of S_h direction. The Figure 11 showing the von mises stress range 69 to 84MPa at the well wall. The compressive hoop stress becomes maximum at the wall and breakout occurs. Zoback et al., 2003 has also indicated the maximum hoop stress at the wall where elongation takes place. The stress vector plot (Figure 12) is indicating the same result as in figure 9.

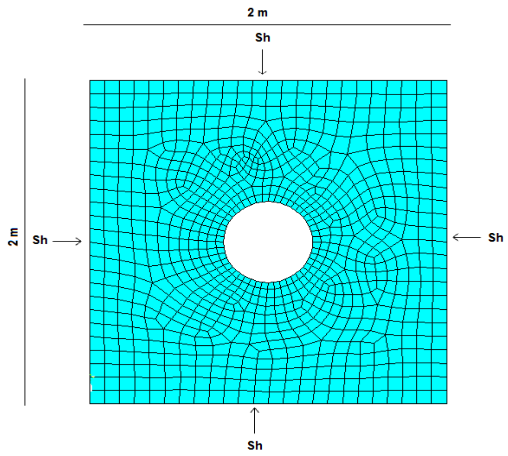

Figure 1: Finite element mesh and boundary condition for 2D model under equal horizontal compressive stresses.

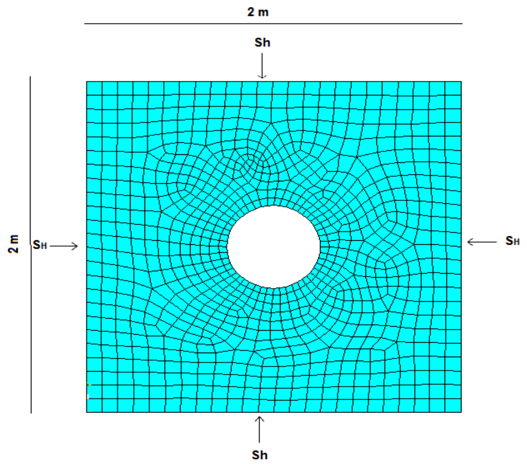

Figure 2: Boundary condition for 2D model under differential compressive stresses.

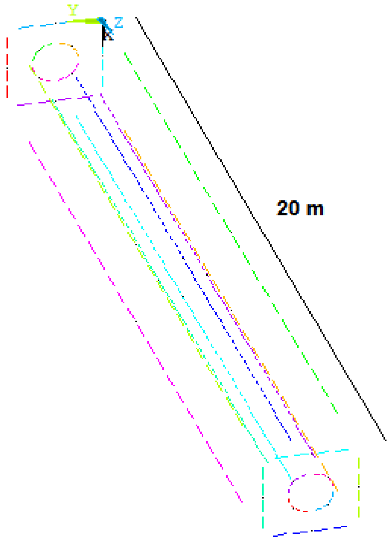

Figure 3: Boundary condition for 3D model under differential compressive stresses.

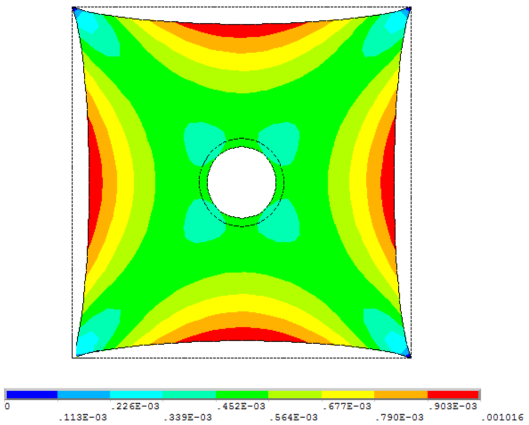

Fig. 4: Resultant displacement for 2D model under equal horizontal compressive stresses.

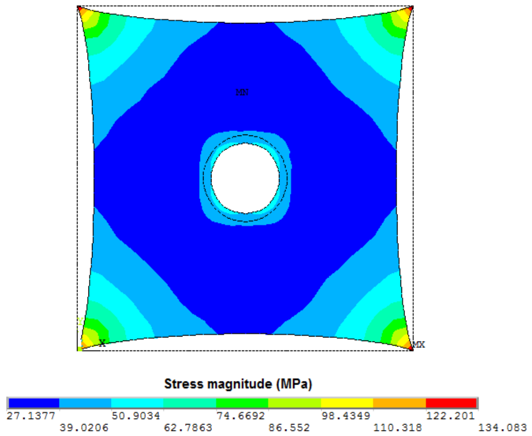

Figure 5: Von mises stress contour for 2D model under equal horizontal compressive stresses

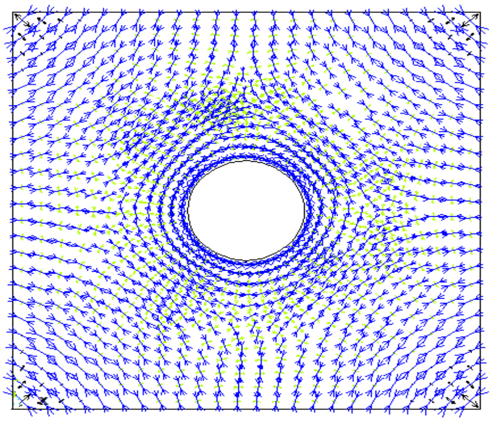

Fig. 6: Principal stress vector plot 2D model under equal horizontal compressive stresses.

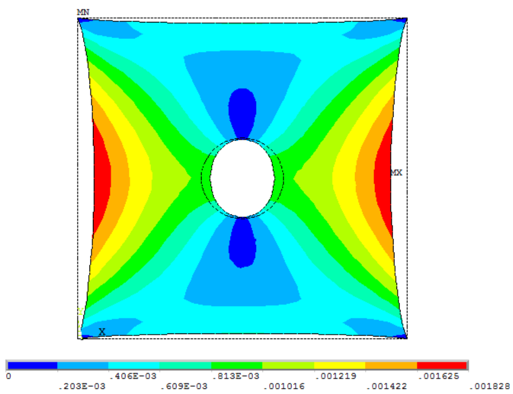

Figure 7: Resultant displacement for 2D model under differential horizontal compressive stresses.

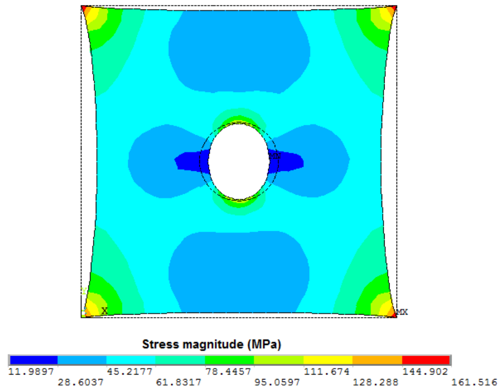

Fig. 8: Von mises stress contour for 2D model under differential horizontal compressive stresses. Compressive hoop stress is maximum at the direction of far-field S_h direction.

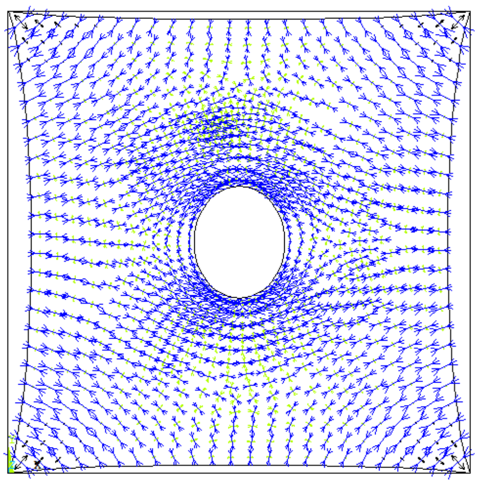

Figure 9: Principal stress vector plot 2D model under differential horizontal compressive stresses. Green and blue colour presents the minimum and maximum horizontal principal stress direction.

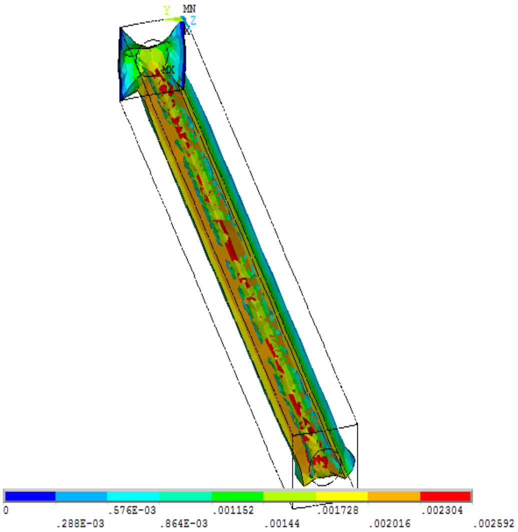

Fig. 10: Resultant displacement for 3D model under differential horizontal compressive stresses.

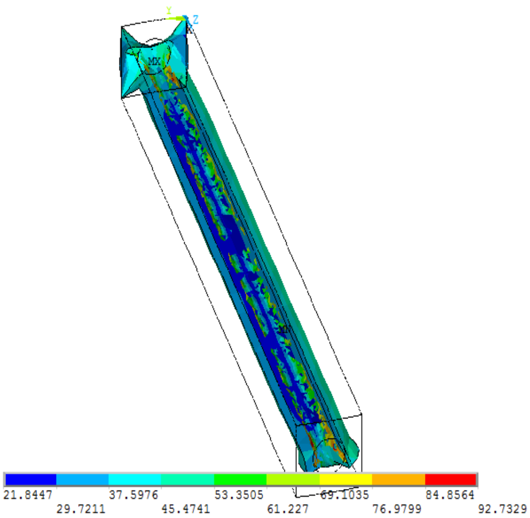

Figure 12: Von mises stress contour for 3D model under differential horizontal compressive stresses. Compressive hoop stress is maximum at the direction of far-field S_h direction.

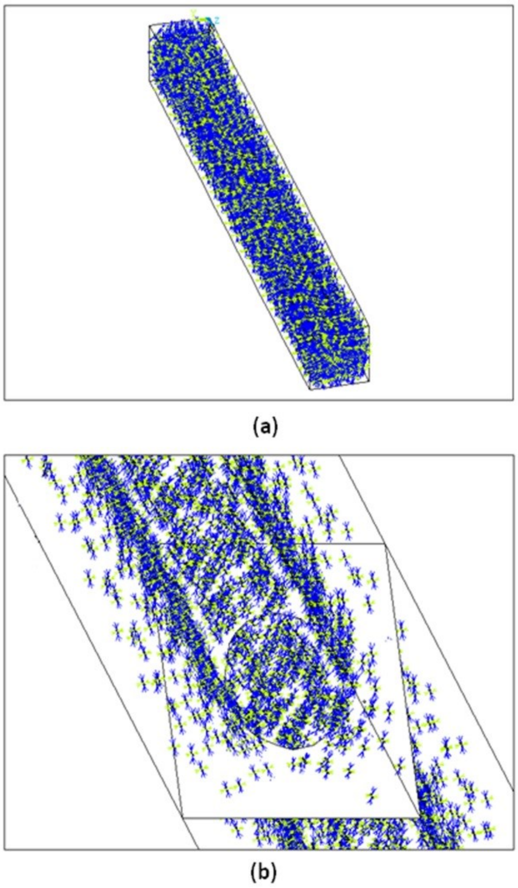

Figure 11: (a) Principal stress vector plot 3D model under differential horizontal compressive stresses. Green and blue colour presents the minimum and maximum horizontal principal stress direction. (b) Principal stress vector plot at a horizontal section for the square block.

Validation of Model

Zoback et al., 2003 has discussed the elongation of borehole under differential stresses through image logs like Ultrasonic Televiewer and Formation Micro Imager. Figure 12 is showing borehole elongation at two wells. Breakouts are observed as dark bands (low reflection amplitudes) on opposite sides of the well in ultrasonic televiewer image logs (well A) and out-of-focus zones on electrical imaging logs (well B). Our model output also indicates similar results as illustrated in figure 12.

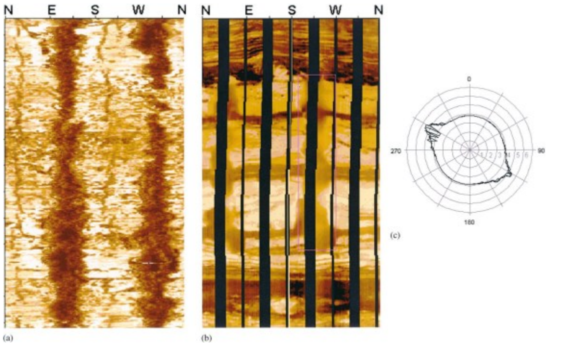

Figure 12: Illustrates borehole breakout in (a) ultrasonic televiewer image log in well A and (b) Formation micro imager, FMI log in well B along with elliptical section of well A (after Zoback et al., 2003).

Conclusions

This exercise demonstrates the wellbore deformation under equal and differential far-field horizontal compressive stresses. The model predicted deformation indicates that the wellbore diameter is increased along the application of minimum horizontal stress and is shortened towards the direction of maximum horizontal stress. Spalling off around the wellbore wall will occur under this breakout condition. The stress vector plots indicate that the breakout direction will provide the orientation of S_h around any well. Modeling results are validated with the image logs for two wells.

References

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